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Relationship between Balsam woolly adelgid Damage, Radial Growth, Climate and Stand Characteristics in Eastern Maine

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RELATIONSHIPS BETWEEN BALSAM WOOLLY ADELGID DAMAGE, RADIAL GROWTH, CLIMATE AND STAND CHARACTERISTICS IN EASTERN MAINE

By

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A THESIS

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IN EASTERN MAINE

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Thesis Advisor: Dr. William H. Livingston

An Abstract of the Thesis Presented
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Balsam woolly adelgid (BWA) (*Adelges piceae*) is an insect pest of fir (*Abies* spp.) that was introduced to Maine in the early 1900's. Within 50 years, it was found across the southern half of the state. BWA continued to kill balsam fir (*Abies balsamea*) in coastal sections of Maine but damage inland has been sporadic and scattered. Within the last decade increases in BWA damage severity and related fir mortality were reported in interior eastern Maine.

This study investigated if the onset of BWA-related growth decline was a recent event; if climate trends coincided with growth reduction in BWA infested trees; and if damage severity varied with site and stand characteristics. Data were collected from 29-0.08 ha (1/5th acre) plots in 3 eastern Maine climate zones. Increment cores of BWA-infested balsam fir and a nonhost species, and several tree and plot measurements, were

gathered on each plot. Trees were divided into three groups for analysis, less affected fir (no dieback), more affected fir (have dieback) and nonhost.

Three-year growth trends of the more affected fir were compared with the less affected fir and the nonhost. For the period of record there was no time when the more affected fir had significantly ($P<0.10$) reduced growth in comparison to the less affected fir on a region-wide basis. However, beginning in 1998 and continuing through 2001 growth trends of the more affected fir were significantly ($P<0.10$) less than nonhost trends region-wide.

A chronology of rotholz occurrence suggests a buildup of adelgid populations from the late 1980's continuing through 2003. Lethal temperatures for BWA in the study area have been less frequent since the 1940's. It appears there has not been sufficient cold to appreciably slow the increase of adelgid populations since this time. An additional stress, the drought of 2001, coincided with a spike in fir mortality.

Damage severity was positively correlated with age, negatively correlated with density and uncorrelated with latitude rank (which was used as a surrogate for climate zone). Damage severities between site classes based on soil-drainage were not significantly different ($P<0.10$). Mean diameter, height, age and uncompacted live crown ratio between less affected and more affected fir groups by plot were not consistently different.

The study's results indicate that given time, lack of competition for fir from other agents (e.g. spruce budworm) and a continuation of current climate conditions, adelgid populations will build up in the region of the study regardless of site and stand characteristics. Monitoring the condition of stands known to be infested with BWA is an important activity for managers. Management decisions need not be immediate as trees survive adelgid infestation for some time. However, productivity of affected stands will decrease and shorter rotations may be justified. Affected stands nearing merchantable size should be examined soon after a drought event because of the possible need to salvage dead trees.

Unless lethal winter temperatures occur, BWA will continue to infest balsam fir stands and increase its damage as trees mature in eastern Maine.

DEDICATION

In memory of Sara Mae Bush
Friend, Sister, Scholar, Scientist
(May 14, 1972 to June 22, 2000)

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Introduction

Background

Balsam fir (*Abies balsamea*) is a major component of the forests in the northeastern United States and southeastern Canada and is an economically and ecologically important species in Maine (Bakuzis and Hansen 1965, Field 1980, Frank 1990). The Forest Inventory and Analysis results from the 1998 to 2003 measurement cycle show that it is the most abundant commercial tree species in Maine (McWilliams *et al*. 2005). Balsam fir is an important pulp species and is also used for light framing and specialty products such as wreaths, Christmas trees, and fragrant sachets (Bakuzis and Hansen 1965, Frank 1990).

The balsam woolly adelgid (BWA), *Adelges piceae,* is one of several insect pests of balsam fir. BWA was introduced to North America, most likely on nursery stock received in Maine and Nova Scotia in the early 1900's (Felt 1910, Kotinsky 1916, Hain 1988). While it does not cause significant damage to its native European host, silver fir (*Abies alba*), it can damage and lead to the mortality of North American true firs (*Abies* spp.) (Hain 1988, Hain *et al.* 1991). Its host species is balsam fir in the Maritime Provinces of Canada, the eastern third of New York State and much of Maine, New Hampshire and Vermont. Separate introductions have occurred in the southeastern United States and in western North America. BWA is the most significant damaging agent of Fraser fir (*A. fraseri*) throughout its range in the Southeast (Beck 1990). The adelgid is also a problem in coastal Oregon, Washington and British Columbia; primarily on Pacific silver (*A. amabilis*), grand (*A. grandis*), and subalpine (*A. lasiocarpa*) firs (Doerskin and Mitchell 1965, Mitchell *et al.* 1970, Hain 1988). Spread of the adelgid to interior portions of North America seems to be checked by colder continental climates (Greenbank 1970).

Within fifty years of its introduction to Maine, the BWA was found across the southern half of the state with the most severe infestations east of the Penobscot River within 50 km of the coast (Brower 1947). A review of the 20th century Maine Forest Commissioner's Biennial Reports reveals that BWA continued to kill balsam fir in coastal sections of Maine; but damage inland has been sporadic and widely scattered (Maine Forest Service, Augusta, ME). However, within the last decade increases in severity of BWA damage and fir mortality have been reported in interior eastern Maine. This increase was first noted in the Maine Forest Insect and Disease Summary in 2000 (Dearborn and Granger 2001). The 2003 inventory report noted a shift in fir mortality from a concentration in northern Maine in the 80's and 90's to the central region in 2003, possibly reflecting a change in the sources of mortality. Additionally, almost 21 percent of balsam fir plots had at least 10 percent basal area with poor crowns in the latest inventory (McWilliams *et al.* 2005); symptoms consistent with those resulting from increased BWA damage (Hain 1988).

In 2003 the Maine Forest Service entered into a cooperative agreement with the Forest Health Protection program of the U.S. Forest Service to investigate the impact of BWA on balsam fir stands in Maine. This study was developed as a part of that agreement and used dendrochronology to investigate if recent intensification of BWA corresponds to (i) distinct weather patterns such as warm winters or droughts and to (ii) site factors. Background information needed for the study included biology of the insect, tree, and their interactions, and use of dendrochronology to evaluate past pest outbreaks.

Balsam Woolly Adelgid Classification

BWA is classified in the family Adelgidae, superfamily Aphidoidea, suborder Sternorrhyncha, and order Hemiptera (Triplehorn and Johnson 2005). Hemipterans have piercing-sucking mouthparts consisting of a food channel and a salivary channel formed at the boundary of the two maxillae. These maxillae are abutted by the mandibles and together are called stylets. The stylets are sheathed by the labium and are used to inject saliva into host tissue and extract a food slurry (Triplehorn and Johnson 2005).

The insects in the suborder Sternorrhyncha are usually sedentary throughout much of their lifecycle. The BWA spends most of its lifecycle attached to the host tree by its stylets. Species in the family Adelgidae feed only on sap of conifers (Carter 1971, Triplehorn and Johnson 2005). Most adelgids have a complex life cycle involving a primary and a secondary host. However, BWA has a single host in its life cycle: a true fir (Carter 1971, Hain 1988). Balsam woolly adelgids, formerly called aphids, differ from aphids in several ways including lacking cornicles and shorter antennal segments (Carter 1971, Hain *et al.* 1991).

Balsam Woolly Adelgid Life History

BWA undergoes gradual metamorphosis and has several life stages including egg, three larval instars and adult. There are only females in North American populations, and reproduction is parthenogenetic. Two complete generations occur per year in Maine (Brower 1947). Overwintering first instar larvae become active in late April or early May. They molt into the second and third instars then adults. In Maine, adults begin oviposition in early- to mid-May (Brower 1947, Balch 1952). They deposit clusters of up to 248 amber-colored eggs in dense woolly mats. In one to two weeks crawlers, the only mobile stage of the insect, emerge from the eggs (Brower 1947). Crawlers locate feeding sites and insert their stylets, usually attaching near bark lenticels, roughened areas, at branch nodes or at the base of buds especially in the most recent 3 years of growth (Hain 1988, Bryant 1974). Then, without molting, they change into a wax-fringed resting stage called the neosistentes (neosistens, singular) (Hain 1988). The neosistentes enter summer diapause, or aestivation, which lasts from 4 to 7 weeks (Greenbank 1970). After leaving diapause they go through three molts resulting in the second and third instars and then the adults. All three of these stages are covered in a dense white waxy material secreted from pores on the insect body. This generation of adults oviposits from mid-July forward. Second generation crawlers are abundant in mid-September (Brower 1947). After these crawlers settle, they transform to the neosistentes and enter winter diapause. All other life stages present at the onset of winter die from exposure to cold (Greenbank 1970, Mitchell *et al.* 1970, Hain 1988).

Dispersal occurs in the egg and crawler stages. Wind is the primary dispersing agent of crawlers, distributing insects within and between stands. Individuals at forest edges may be most important for longer-range wind dispersal (Atkins and Hall 1969). Dispersal is also achieved through transfer of eggs and crawlers by small animals such as insects, small mammals and amphibians (Hain 1988). Humans play a role in movement as well through transportation of infested materials (Atkins and Woods 1968). Some crawlers may scatter by dropping from the tree or being washed by rain; these are able to travel short distances and could be responsible for some within stand spread (Balch 1952).

Crawlers that disperse tend to settle on main stems and large branches or in the outer parts of the crown (Hain 1988). Bryant (1971, 1976) found that crawlers in crowns tended to settle at the base of needles, in staminate flowers and in the nodes and internodes of the 2-6 year old growth in the second quarter from the top of the crown. They generally do not settle on the newest growth (Bryant 1974) and virtually all crawlers settle in crevices (Bryant 1976).

Balsam Woolly Adelgid Mortality Factors

Survival of BWA is influenced by climate, predators, and other mortality factors. Severe winters can result in periodic reductions in adelgid densities. Low winter temperatures below -34º C (-30º F) will instantaneously kill diapausing neosistentes; other stages are killed at temperatures around freezing (Balch 1952). At temperatures above -34º C, duration of a temperature event affects the amount of mortality within a population. For example, cold-hardy first instars exposed to temperatures of -30º C in a laboratory had an instantaneous mortality of about 40 percent. After 24 hours of exposure mortality had reached about 60 percent. Beyond that, mortality increased linearly at a rate of 5 percent per day until day 5 when it reached an asymptote at approximately 80 percent mortality (Greenbank 1970). Mortality of cold hardy neosistentes will occur with prolonged exposure to temperatures as high as -20.5º C (5º F) (Clark *et al.* 1971) Survival may be higher in winters with deeper snow pack because individuals below snowline are insulated from lethal temperatures (Greenbank 1970). Greenbank found with air temperatures as low as -28.9º C (-20º F), bark temperatures approximately 45 cm (18 in.) beneath the snow did not drop below -6.7º C (20º F); and with snow cover of approximately 15 cm (6 in.) bark temperature did not drop below -18º C (0º F) (Greenbank1970).

Early fall frosts, before the insects have fully entered diapause and become freeze tolerant can cause high mortality; as can late spring frosts, after the insects have left diapause and broken dormancy (Greenbank 1970, Hain 1988).

High temperatures may cause some mortality, but many individuals are adequately protected from these events by micro-habitat (Balch 1952). Those that settle in exposed locations are soon eliminated by lethal bark temperatures (Greenbank 1970).

BWA has several predators, both native and introduced, in North America. Mortality caused by these predators is not generally high enough to prevent damage by adelgid (Mitchell *et al.* 1970). Some occasional to frequent native predators include species in the families Trombididae (mites), Hemerobiidae (brown lacewings), Miridae (plant bugs), Coccinellidae (ladybird beetles), and Syrphidae (hover flies) (Balch 1952, Clark *et al.* 1971, Triplehorn and Johnson 2005). Non-native predators released for biological control include *Laricobius erichsonii* (a tooth-necked fungus beetle, Derodontidae), *Aphidecta obliterata* (Coccinellidae), *Pullus impexus* (Coccinellidae), *Aphidoletes thompsonii* (a gall midge, Cecidomyiidae), and *Neoleucopis obscura* (an aphid fly, Chamaemyiidae) (Carol and Bryant 1960, Clark *et al.* 1971, Triplehorn and Johnson 2005).

In general, native and introduced predators do not respond to increases in prey density sufficient to control adelgid populations (Greenbank 1970). Many of the native predators are stage specific and do not feed on the crawlers. Others are generalists and feed on many insect species (Caroll and Bryant 1960). The non-native predators tend to be inefficient because they are adapted to feeding on stem populations, rather than twig populations (Carroll and Bryant 1960). Some are not adapted to extremes in cold and do not overwinter successfully in high enough numbers to effectively control adelgid populations (Caroll and Bryant 1970). Others are heavily parasitized so their populations are restricted such that their impacts as bio-control agents are limited (Balch 1952, Caroll and Bryant 1960).

Dispersal is a significant source of mortality in BWA populations. In populations on two trees, Greenbank (1970) found that 50 to 80 percent of crawlers died due to dispersal, and Amman (1970) found 68% loss to dispersal in spring and 18% in summer.

Additionally, tree condition can influence adelgid survival. Amman (1970) found a negative relationship between percent survival and radial growth of trees at the time of infestation. A positive relationship exists between tree vigor prior to infestation (as expressed by radial growth prior to infestation) and BWA population density during infestation (Amman 1970). This indicates that more vigorous trees should initially support a denser population of adelgid which would lead to more injury. As an infestation progressed, radial growth would be reduced, leading to higher survival of BWA, followed by tree decline and die-off of adelgid populations (Amman 1970).

Symptoms and Damage

BWA infestations exhibit two general forms: stem and crown phases. On balsam fir stem phase dominates in colder climates. In moderate climates, stem phase is most noticeable in newer infestations, whereas crown infestations become more apparent in older infestations (Carroll and Bryant 1960, Greenbank 1970). Both phases of infestation lead to changes in the tissues surrounding the feeding site. Changes in wood and bark tissue commence upon insertion of adelgid stylets and are observed regardless of further survival of the insect (Balch 1932, Balch 1952). Stylets are inserted intercellularly in parenchyma of the cortex and phelloderm (Balch 1952). This causes enlargement and proliferation of cells in the surrounding tissues. Xylem adjacent to feeding sites is often reddish in color, highly lignified and has a reduced ability to transport fluids (Balch 1952, Hain 1988, Smith and Nicholas 2000). This characteristic tissue is called rotholz, German for redwood. Growth rings containing rotholz may be wide in comparison to normal rings, and rotholz often extends downward from the point of feeding (Schooley and Bryant 1978). Rotholz can be localized within a growth ring, not affecting the entire circumference of the stem (Balch 1952, Hain 1988).

Stem-infested trees have regions of rotholz adjacent to areas where adelgids fed. Because of the profusion of cells and production of abnormally large cells, these regions may initially bulge out from the neighboring stem tissues (Hain 1988). Physiological drought results from the interruption of water transport due to rotholz formation (Hain 1988) leading to needle loss, thin crowns and top dieback (Mitchell *et al.*1970). Stem infestations usually bring about mortality more rapidly than crown infestations (Hain 1988), with death following moderate to severe infestations occurring within 3 years. Crown phase infestations often last two decades or more (Brower 1947, Carroll and Bryant 1960).

Symptoms of crown infestation include gouting, needle mortality, rotholz formation, and crown thinning, deformity and dieback from the top down (Hain 1988, Greenbank 1970, Mitchell *et al.* 1970). Swollen branch nodes and stunted terminal growth characterize gouting (Hain 1988). In trees with infested crowns new needles are not created because the buds are inhibited, resulting in a loss of photosynthesizing capacity, and gradual starvation of the tree (Mitchell et al. 1970, Greenbank 1970). Crown infestation can lead to reduced growth and sometimes death (Hain 1988).

BWA infestations can lead to increased occurrence of root rot and windthrow in balsam fir. Some stands lose most of the dominant and co-dominant fir (Greenbank 1970). Economic impacts include loss of yield and loss of value caused by the production of rotholz. Rotholz can result in more brittle lumber products and is less desirable as a pulp product (Bakuzis and Hansen 1965).

Factors Predisposing Fir to Balsam Woolly Adelgid Damage

North American fir are highly susceptible to injury from adelgid, however several factors influence the likelihood and severity of injury. Tree and stand characteristics along with climate and site are of primary importance in influencing infestation patterns.

Stand age and infestation history may influence adelgid populations. Initial infestations usually occur on taller, larger diameter trees (Balch 1952, Bakuzis and Hansen 1965, Johnson *et al.* 1963, Greenbank 1970). Smooth-barked trees are less susceptible than rough-barked, small diameter trees are less susceptible than large, and trees in younger, denser stands are less susceptible than older, open grown trees (Greenbank 1970). Crown infestations have been observed on stands as young as six years at the stump (Schooley and Oldford 1974, Schooley and Bryant 1978), but as a stand nears 30 to 40 years of age populations tend to move from crowns onto stems where more serious damage occurs (Greenbank 1970).

A tree's suitability as a food source changes as an infestation progresses. Initially, increased concentrations of proteins at areas of active feeding create microsites which are more nutritious, leading to a locally expanding population (Kloft 1957, Hain 1988). Eventually, depletion of nutrients or development of impermeable outer bark around feeding zones make the area less nutritious or unavailable for feeding and adelgid populations on an individual tree or in a particular area of the stem may collapse (Kloft 1957, Greenbank 1970, Mitchell *et al.* 1970, Hain 1988).

Climate influences the development and progression of infestations mostly through the impact of temperature on BWA mortality (Greenbank 1970). In more moderate climates a few large diameter trees are killed as a result of initial stem infestation, and most overstory trees are eventually killed or severely damaged as a result of a combination of stem and trunk infestations. In colder interior climates, populations tend to be restricted to lower stems, with crown infestations usually being killed annually by cold winter temperatures. There is in general less tree mortality in interior regions where winter low temperatures are colder (Greenbank 1970).

Site may affect the degree of damage incurred in a stand (Hain 1988). Balsam fir is found on a wide range of sites in Maine. These include a variety of formerly glaciated inorganic and organic soils (Frank 1990) ranging in texture from clay, to sand, to loam and peat (Bakuzis and Hansen 1965). Soil pH varies widely, but fir thrives where the pH of the organic layer is between 6.5 and 7.0 (Frank 1990, Bakuzis and Hansen 1965). Soil moisture appears to be a key factor in balsam fir's ability to compete; it does not do as well on sites prone to drought (Bakuzis and Hansen 1965). Balsam fir also does not compete well on premium sites (Bakuzis and Hansen 1965).

In Maine, Brower (1947) observed that unfavorable sites for balsam fir served as population centers for adelgid; severe damage occurred on wet, poorly drained soils and heavy clays. He also reported severe damage on ledges with thin soils, edges of roads and cut stands. Unopened stands had light to no adelgid damage (Brower 1947).

In Newfoundland on balsam fir Page (1975) found more damage on dry to mesic sites than on mesic to wet sites. Higher levels of damage were also associated with steeper slopes, rocky knolls, soils with shallow humus layers, and coarse-textured soils (Page 1975, Schooley and Bryant 1978). More severe damage may occur on these sites as a result of drought-prone soil amplifying the physiological drought brought on by change in wood structures (Schooley and Bryant 1978).

In Pacific silver fir (*Abies amabilis*), Johnson *et al.* (1963) found that damage was greatest in stands with the most stem infestations. Higher occurrence of stem infestations tended to correspond with high site quality (site quality being determined using site index curves for grand fir (*Abies grandis*)). The more vigorous trees on high quality sites may have higher levels of damage because they supply the best nutrition to the adelgid, allowing populations to build rapidly (Hain 1988).

Dendroecology for Detecting Insect Outbreaks

Tree-ring widths vary in response to the tree's environment. This year to year variability is referred to as sensitivity. Ring width may be impacted by several aspects of a tree's surroundings including precipitation, temperature, insect feeding and competition. How much one of these variables will impact a particular tree is dependent on the type of environment in which the tree exists: trees in extremely dry environments tend to be sensitive to drought, near tree-line trees often respond to cold winter temperatures (Fritts 1971). In studies of insect defoliation to minimize differences in ring width between the host and nonhost species ring-widths due to factors other than the insect of interest it is important to select trees on homogenous sites of similar age and crown positions (Swetnam *et al.* 1987).

Dendrochronology, the use of information from cross-dated tree-ring series, has been applied in many branches of science (Fritts 1971, Fritts and Swetnam 1989). A cross-dated tree-ring series is a precisely dated series as opposed to a series dated by counting rings, in which dates are estimates. Cross-dating is achieved by using the variability of tree-rings within series and consistency in patterns of variability between series to assign an exact year of formation to each ring (Fritts and Swetnam 1989). Cross-dating allows the detection of missing and false rings, and mistakes in counting and measurement. This is especially important in studies involving stressed trees where locally missing rings may be a problem (Fritts and Swetnam 1989). Pilcher (1990) cautions that cross-dating may not be accurate or possible in short series and states that cross-dating in series with lengths of less than 40 years may be suspect.

Trees with high variation in ring widths are said to be sensitive whereas those with relatively consistent widths are complacent (Fritts 1971). Trees in arid regions tend to be sensitive, and dendrochronology has been used extensively and highly successfully in these regions. Dendrochronology has been successfully applied in less extreme climates as well; however it can be more complicated in cases where ring series tend to be complacent (Stokes and Smiley 1996).

Cook (1987) described ring width as a function of age, climate, disturbance and unexplained variability. Disturbance in his function could both be local and originating within the stand (endogenous); and/or stand-wide and originating from outside the stand (exogenous). Tree-ring series are standardized in an attempt to remove the age component as well as the sources of variation that are not relevant to the objectives of the study (Cook 1987). This standardization also stabilizes the series—giving it a mean of approximately one and a constant variance which allows series to be averaged together (Cook *et al.* 1990).

Dendroecology is the use of dendrochronology in studies of ecological problems (Fritts and Swetnam 1989). Investigators using dendroecology are usually interested in teasing out the disturbance portion of the ring width formula described by Cook (1987). Past dendroecological studies of insect defoliators (Eckstein et al. 1991, Morin et al. 1992, Swetnam and Lynch 1993, Jardon et al. 1994, Mason et al. 1997, Speer et al. 2001) have compared standardized host and nonhost tree chronologies to separate the impacts of insects on tree growth from the impacts of other factors such as climate and competition; a technique first developed to study the impacts of air pollution (Nash *et al.* 1975). This method assumes that nonhost and host trees will show similar responses to factors such as climate (Swetnam *et al.* 1987). The primary objectives of these studies were to examine changes in periodicity of outbreak cycles, severity of outbreaks, and/or extending the knowledge of outbreaks to times pre-dating historical records.

<u>Hypotheses</u>

Based on the above information, the following hypotheses were developed for this study. First, recent intensification of BWA has initiated reductions in radial growth just within the last decade—as indicated by casual observation of mortality timing. This was tested by studying tree-ring patterns of balsam fir and nonhost species in eastern Maine. Second, onset of growth reductions on adelgid infested trees corresponds to distinct weather patterns, such as warm winters or droughts, based on examination of climate records. Finally, BWA damage severity varies with site class and other stand characteristics.

Methods

Study Area

Study plots were established in Penobscot, Hancock and Washington counties in eastern Maine (Figure 1) in climate zones 7, 5 and 4 (from south to north) as delineated by Briggs and Lemin (1992). In climate zones 7 and 5, plots were established on property then owned by International Paper Company. To supplement the available land base in climate zone 4, plots were established on property owned by Baskahegan Corporation and on non-industrial private forest land. The population of interest was stands containing at least 12 fir in the upper canopy exhibiting adelgid-related crown dieback and at least 12 acceptable nonhost trees with crowns within the upper canopy. Stands were only used in this study if (i) direct evidence of adelgid (either insects on trunks or gouted twigs within 6 feet of the ground) could be found and (ii) the site was homogeneous.

A total of 29 fixed radius 0.08 hectare plots (1/5th acre) were randomly located in 27 townships in eastern Maine (Table 1). One plot was established per township except in climate zone 4 where there was less industrial forest land; the townships of Kossuth and Topsfield had two plots each on opposite sides (east and west) of the towns.

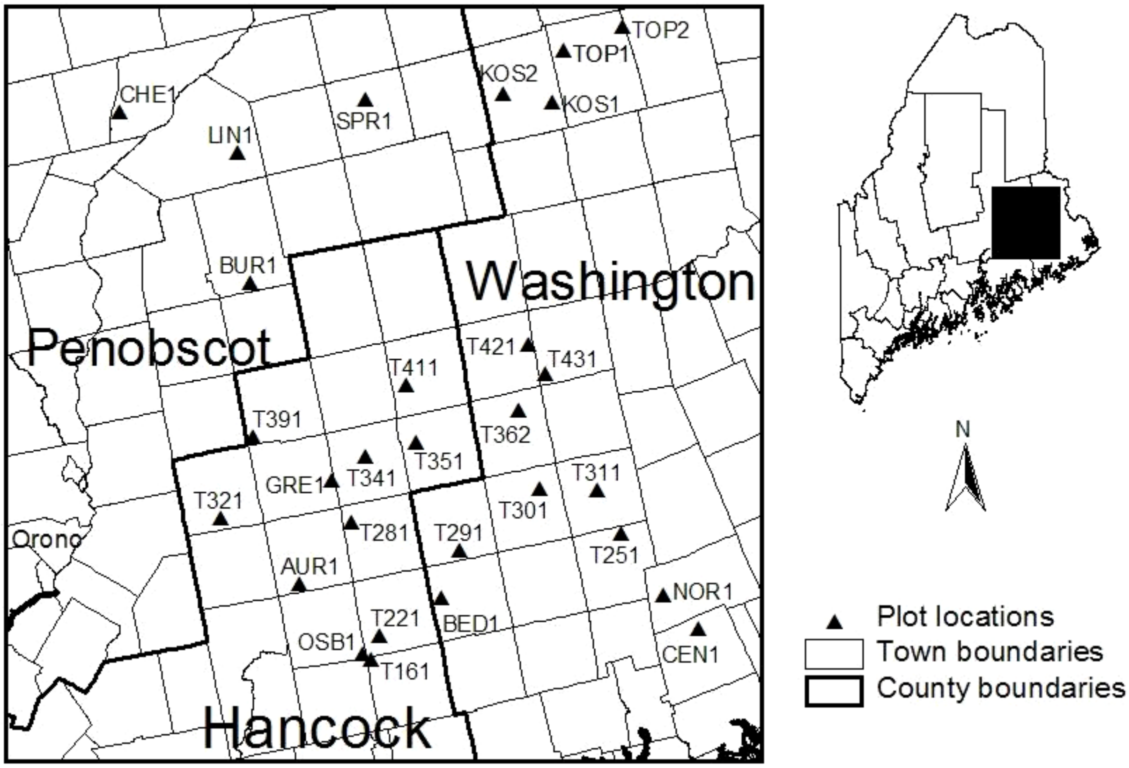


Figure 1. Overview of plot locations. GIS layers for county and town boundaries acquired from Maine Office of GIS Office of Information Technology, Department of Administrative and Financial Services, Augusta, ME.

Table 1. Plot locations. Ordered by climate zone and alphabetically by plot. Climate zones delineated by Briggs and Lemin (1992).

Climate Zone	Plot	Township	County	Latitude	Longitude
4	CHE1	Chester	Penobscot	45° 23' 43.4"	-68° 35' 10.7"
4	KOS1	Kossuth Twp	Washington	45° 24' 10.7"	-67° 51' 31.3"
4	KOS2	Kossuth Twp	Washington	45° 24' 45.0"	-67° 56' 29.8"
4	LIN1	Lincoln	Penobscot	45° 20' 45.2"	-68° 23' 22.2"
4	SPR1	Springfield	Penobscot	45° 24' 30.1"	-68° 10' 24.2"
4	TOP1	Topsfield	Washington	45° 27' 50.1"	-67° 50' 17.9"
4	TOP2	Topsfield	Washington	45° 29' 28.0"	-67° 44' 13.6"
5	BUR1	Burlington	Penobscot	45° 11' 29.9"	-68° 22' 11.6"
5	GRE1	Great Pond	Hancock	44° 57' 20.2"	-68° 14' 48.5"
5	T341	T34 MD	Hancock	44° 58' 59.2"	-68° 10' 46.2"
5	T351	T35 MD	Hancock	44° 59' 58.8"	-68° 05' 39.5"
5	T362	T36 MD BPP	Washington	45° 02' 08.6"	-67° 55' 21.7"
5	T391	T39 MD	Hancock	45° 00' 30.6"	-68° 21' 56.5"
5	T411	T41 MD	Hancock	45° 04' 06.4"	-68° 06' 34.9"
5	T421	T42 MD BPP	Washington	45° 06' 51.0"	-67° 54' 16.2"
5	T431	T43 MD BPP	Washington	45° 04' 47.4"	-67° 52' 36.8"
7	AUR1	Aurora	Hancock	44° 49' 56.0"	-68° 17' 25.8"
7	BED1	Beddington	Washington	44° 48' 51.8"	-68° 03' 12.6"
7	CEN1	Centerville	Washington	44° 46' 22.0"	-67° 37' 36.1"
7	NOR1	Northfield	Washington	44° 48' 47.3"	-67° 41' 36.2"
7	OSB1	Osborn	Hancock	44° 44' 53.1"	-68° 11' 09.6"
7	T161	T16 MD	Hancock	44° 44' 27.1"	-68° 10' 19.9"
7	T221	T22 MD	Hancock	44° 46' 14.1"	-68° 09' 27.7"
7	T251	T25 MD BPP	Washington	44° 53' 14.2"	-67° 45' 12.6"
7	T281	T28 MD	Hancock	44° 54' 18.9"	-68° 12' 08.6"
7	T291	Devereaux Twp	Washington	44° 52' 13.8"	-68° 01' 24.6"
7	T301	T30 MD BPP	Washington	44° 56' 32.0"	-67° 53' 15.7"
7	T311	T31 MD BPP	Washington	44° 56' 22.8"	-67° 47' 33.7"
7	T321	T32 MD	Hancock	44° 54' 44.6"	-68° 25' 08.8"

Sampling

Sampling was conducted between May 2004 and May 2005, with the bulk of sampling completed in the summer of 2004. To locate candidate stands, a point was randomly selected in each township with industrial ownership. Drivable roads were taken as close as possible to the random point, and roads and stands were explored moving away from that coordinate. The first appropriate stand encountered was used for the study plot location. Several townships lacked suitable stands. In one town (Lincoln), industrial ownership was limited and permission to use the first appropriate stand encountered was received from the owner. Plot centers were established close to the center of the side of the stand adjacent to the road and at least two tree heights from the road on an azimuth approximately perpendicular to the heading of the road.

Plot level variables included date, location, elevation, slope, aspect, site class and seedling and sapling damage. A geographic positioning device was used to determine the coordinates of each plot center. The average slope and aspect of the plot was measured from plot center using a clinometer and compass. Site class was assigned based on assessment of depth to mottling and rooting depth in a soil pit using Briggs' (1994) classification system. Site class was recorded on a scale of 1 to 5 with 1 corresponding to the most productive, driest sites and 5 to the least productive, wettest sites (Briggs 1994). Seedling and sapling damages were assessed on the basis of the entire plot. If the majority of seedlings or saplings were alive and gouting was found then damage was recorded as gout. If the majority of seedlings or saplings were dead and exhibiting gout, damage was recorded as mortality.

Procedures for measuring tree level variables are described in the Northeastern Research Station Forest Inventory and Analysis Field Guide (USDA Forest Service, 2003). Data collected for all fir trees at least 12.6 cm diameter at breast height (dbh) included dbh, tree condition, total height, crown class, uncompacted live crown ratio, crown density, dieback and transparency. Dbh and height were recorded for all standing dead fir at least 12.6 cm dbh; and dbh and crown class were recorded for all nonhost trees. Species and dbh were recorded for remaining live trees at least 12.6 cm dbh.

Adelgid-related variables were adapted from damage assessments developed for the Maine Forest Service by Henry Trial Jr. (described in USDA Forest Service, 2003). Trunk phase was recorded for all live fir. It is a rough snapshot of the presence and abundance of BWA on the first 1.8 m (6 ft) of the trunk with categories of: 1) absent, 2) trace, 3) light, 4) heavy. Tree status indicates whether a fir was 1) alive, 2) dead due to adelgid or 3) dead due to other causes. Top condition describes the general shape of a fir's crown. Categories of tops are: 1) no symptom, 2) gout with no twig mortality, 3) live, deformed top, 4) live, top with discontinuous green foliage, 5) dead tree with a normal top or 6) dead tree with a deformed top. BWA damage indicates the severity of adelgid-related damage with 8 categories. Categories of BWA damage are: 1) none, 2) gout with no mortality, 3) spired top (gout with suppression of lateral growth), 4) 1-25 percent mortality, 5) 26-50 percent mortality, 6) 51-75 percent mortality and 7) 76-99 percent mortality within the crown and 8) dead.

Two cores were extracted from each dominant or co-dominant balsam fir within the plot. A nonhost species was chosen in each stand, and cores were collected from at least 12 nonhost trees without obvious signs of damage. Where possible, nonhost cores were collected from spruce (*Picea* spp.). It was reasoned these cores would reflect periods of growth suppression related to the spruce budworm (*Choristoneura fumifera*) feeding found in fir cores but not periods of BWA damage. If fewer than 12 trees exhibiting adelgid-related crown dieback or fewer than 12 nonhost trees were found within the plot, additional cores were collected outside the plot radius. These cores were collected from trees within the same stand on sites that resembled the plot area; and were measured as previously described.

Cores were extracted using a 5 mm increment borer. When possible, cores were collected at least 90 degrees apart on the stem. With one exception, extracted samples were transferred to labeled paper or plastic straws for storage. In Township 42 MD many sampled fir were dead and it was expected that upon drying the cores would disintegrate. In this instance cores were mounted directly to grooved wooden blocks in the field using wood glue and masking tape.

Core Processing

After being allowed to air dry for at least 24 hours, the cores were mounted on grooved wooden blocks using wood glue and "clamped" with masking tape. The glue was allowed to dry for at least 24 hours then masking tape was removed and the cores were sanded. Each sample was sanded with 150, 220 and 320 grit sandpapers using a palm sander, followed by hand sanding with 400 grit paper. When necessary, additional hand sanding was done using 800 and 1200 grit papers.

Ring widths of up to 14 trees per stand in each of three groups (less affected fir, more affected fir, and nonhost) were measured using either Windendro (Regent Instruments, Inc., Quebec, QC, Canada) or a Velmex (Velmex Inc., Bloomfield, NY) sliding scale micrometer using Measure J2X software (Voortech consulting, Holderness, NH). The 911 cores that were ultimately measured were selected by assigning a random number to each tree cored, and selecting the subset of up to 14 trees in each tree group assigned the lowest random numbers. The most intact core from each of those trees was used for analysis. For cores that did not intersect the pith, age to pith was estimated using a transparency with concentric circles as described by Applequist (1958).

Analysis

For analysis, trees were classified into three groups: less affected fir were fir with a BWA damage rating of less than 4 (group 1); more affected fir had a BWA damage rating of greater than 3 (group 2); the final group was nonhost trees (group 3). Comparisons between tree groups were completed by plot.

Tree-ring Chronologies

Cores were cross-dated using the list method described by Yamaguchi (1990). Unusually narrow or wide rings, partial rings, false rings, rings with traumatic resin canals and rings containing rotholz were identified for each core and compared among cores. This helped to identify partial and locally absent rings and to assign an accurate date to the rings in each core.

After initial cross-dating, the program COFECHA (Richard Holmes, Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona) was used to identify segments with potential problems in measurement or dating (Holmes 1983). A segment length of 30, the minimum length recommended to avoid false high and low correlation coefficients (Grissino-Mayer, 2001), was used for all runs. This resulted in a critical correlation coefficient of 0.4226 for the 99% confidence level (Grissino-Mayer 2001).

Problem segments identified by COFECHA were re-examined and corrected when necessary. Matching patterns of wide and narrow rings both from the list created in initial cross-dating and from the COFECHA output allowed the last year of growth to be estimated for all dead trees as well.

After all problem sections had been examined and corrected, standardized average chronologies for less affected fir, more affected fir and nonhost were created for each plot by standardizing raw ring widths with a straight line through the mean using the program ARSTAN (Edward R. Cook and Paul J. Krusic, Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, NY). A straight line through the mean was chosen for standardization as it is an effective way to highlight growth below or above the average growth for a tree (Veblen *et al.* 1991).

Both less affected and more affected fir cores were examined for presence of rotholz. Each ring was assigned a value of 0 (no evidence of rotholz); 1 (darkened latewood); 2 (half ring exhibiting rotholz characteristics) or 3 (whole ring showing rotholz characteristics). The percent of fir in a given year showing evidence of rotholz and the cumulative percent of trees having ever exhibited rotholz were calculated. This was considered a reflection of the historic presence and abundance of adelgid. The data were combined across plots and fir groups because of a low number of cores with rotholz in each plot.

To examine growth trends and allow comparison between species, raw ring width chronologies of individual trees were standardized by calculating percent growth change with the equation (modified from Moesswilde 1995, Nowacki and Abrams 1997):

$$GC_x = [((RW_{x+1}+RW_{x+2}+RW_{x+3})-(RW_x+RW_{x-1}+RW_{x-2}))/ (RW_x+RW_{x-1}+RW_{x-2})] *100.$$

Where:

GC_x = Percent growth change for year "x", and

RW_x = Ring width (mm) in year "x".

Because this calculation depends on information from years after the year in question, the length of the series is truncated by the number of years averaged. A 3-year trend was chosen because of our interest in what could be a very recent event. Analyses were carried out on this growth trend information by plot and by tree group (more affected fir, less affected fir, nonhost).

All statistical analyses were completed using SYSTAT 11.0 (Systat Software Inc., Richmond, CA). Normality of the data by tree group (more affected, less affected, nonhost) for each plot by year was evaluated using Shapiro-Wilk test. Tree groups were analyzed only if there were at least 5 in that group on a plot. If one group was not normal ($P<0.01$), then the absolute value of the minimum value plus one was added to all values, and all growth trends for the plot in that given year were log transformed. If log transformations did not achieve a normal distribution ($P>0.01$), then the tree group for that particular plot and year was excluded from the analysis.

One-sided probabilities of the more affected tree group having a mean growth trend less than the less affected or nonhost groups within a given plot and by year were calculated using the GLM procedure. Comparisons between the means were calculated using the Contrast procedure with separate variances. The proportion of plots in a given year with mean growth trends of the more affected fir significantly ($P<0.10$) less than either the less affected fir or the nonhost were calculated. A sign test calculation yielded the probability that the occurrence of reduced growth in the more affected trees was a random event across the study area. One sign test was calculated comparing more affected with less affected fir, and another comparing more affected fir with the nonhost.

Climate Data

Climate data were gathered from several public sources. Data included precipitation, drought and temperature records. Because of the short chronology lengths and the lack of a period in the tree ring record that was not heavily influenced by insect damage, response function analysis was not attempted on this data set. Instead, precipitation and temperature time series were visually compared with the time series created by the ring-width records (ARSTAN, 3 year growth trends, rotholz) to look for associations between ring and climate patterns.

Modeled monthly precipitation values were acquired for each plot from Oregon State University's Spatial Climate Analysis Service (Spatial Climate Analysis Service 2005). Analysis (not shown) indicated that the predicted values were similar to local weather station data. Precipitation amounts were summed for each year, with a given year beginning in November of the previous year and ending October of the year in question. These summed values were standardized by calculating the number of standard deviations each yearly value was from the 110 year average.

As a second indicator of precipitation levels, historic Palmer Drought Severity Indices (PDI) were downloaded for Maine region 2 (NCDC 2005). The PDI is a meteorological drought index that takes into account long-term temperature and precipitation data. It was developed for arid southwest, so does not include snowmelt

(Heim 2002). Values above zero indicate wet periods, below zero, dry. Moderate drought is indicated with values between -2.00 and -2.99, severe between -3.00 and -3.99 and extreme below -4.00. Monthly PDI values were averaged for each year with a given year including the previous-year November through the current-year October.

Temperature data were downloaded for several weather stations within the study area and in areas to the south (where damage is more apparent) and north (where damage is less apparent) to compare the frequency of lethal temperatures to BWA in the last hundred years (NCDC 2005a) (Figure 2).

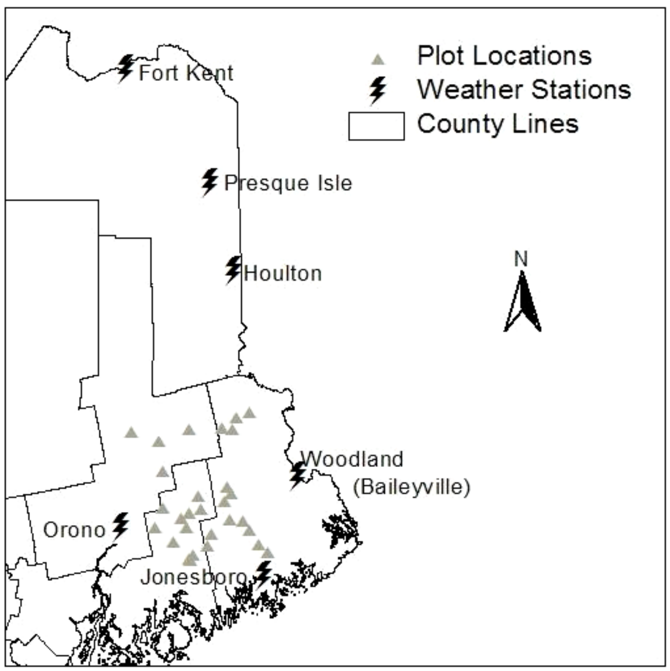


Figure 2. Weather station locations. GIS layer for county boundaries acquired from Maine Office of GIS Office of Information Technology, Department of Administrative and Financial Services, Augusta, ME.

Damage, Plot, and Tree Relationships

Pearson's correlations were used to examine relationships among plot characteristics, among damage characteristics and between plot and damage characteristics For all variables, fit to a normal curve was tested using Shapiro-Wilk test with a cutoff value $P<0.01$ indicating poor fit. Variables whose data did not fit a normal distribution were transformed to meet the normality assumption of the Bartlett Chi-square test statistic for correlation matrices. A significant Bartlett test statistic ($P<0.001$) was considered a good indication that the P-values given for the matrix were valid (Wilkinson *et al.* 2004).

All variables used in this analysis were derived from trees at least 12.6 cm dbh which were located within the plot radius. Plot variables included average age, height and dbh of live fir, basal area of live fir, basal area of all live trees, percent of total basal area in live fir basal area, density of live and recently dead fir, density of live trees ,and rank of latitude (as an indicator of climate zone). DBH was log transformed prior to correlation analysis. A damage severity index was calculated by taking the natural log of the average of the balsam woolly adelgid damage on plots. Other indicators of damage included percent fir (basal area) in the more affected damage group, percent fir (number of stems) with trunk phase, percent of fir cores with rotholz, average uncompacted live crown ratio, average crown density, average transparency, rank of average dieback and rank of percent dead fir.

A factor that has been identified in previous research as having an important influence on BWA damage severity is site (Johnson *et al.* 1963, Page 1975). Site class did not fit well in Pearson's correlations because it is a categorical variable, so its relationship to damage severity was explored separately. A preliminary analysis of variance (ANOVA) using the GLM procedure indicated that mean age was not equal on all sites. Therefore an analysis of covariance (ANCOVA) was performed to compare the damage levels between site classes adjusted for age. The percent of fir basal area (live and recently dead) that had crown dieback (group 2) was calculated. This was used as the response variable as an indication of BWA damage on the plots.

In order to explore factors influencing damage severity at the tree level, a two-sample t-test was used to determine whether the means of several tree measures were different between more and less affected fir. These tests were conducted separately for each plot. Only plots with 5 or more trees in each group were used. Variables were first tested for fit to a normal distribution using a Shapiro-Wilk test and a cutoff value of $P < 0.01$ indicating poor fit. A two-sample t-test was then run using only those plots and variables that were normal or could be log transformed to attain a normal distribution. Measures tested included dbh, height, age, and uncompacted live crown ratio. To limit the risk of type I error, P-values were Bonferroni adjusted for the family of variables (dbh, height, age, live crown ratio) (Chakraborty *et al*. 2004).

Results and Discussion

Study Area

The stands selected for study had diverse histories: they had varying impacts from forest insects and diseases, and past management (Table 2). For example, the spruce budworm impacted the study area in three waves in the 20th century with uneven impacts across the region (Irland *et al.* 1988). Harvesting also influenced present stand condition in a patchy pattern. Many of the sites selected had been harvested within the last several decades as reflected by low stand ages and presence of stumps. Evidence of these events is also found in stand composition and in the tree-ring series.

Seventeen plots were located on well drained site classes; 9 in class 1 and 8 in class 2 (Table A. 1). Nine plots were on somewhat poorly drained sites (class 3) and 3 plots in poorly to excessively poorly drained sites (class 4). Elevations were collected on all but 3 plots and ranged from 60 to 220 meters above sea level. Plots were on flat to rolling terrain, with slopes ranging from 0 to 17 percent and averaging around 5 percent. All stands had evidence of adelgid either on the trunks or on regeneration. One plot (T391) had no fir seedlings or saplings; one had no saplings but had seedlings with gout (T431); the remaining 27 had gouting present on seedlings and saplings. On 2 of the 27 plots mortality dominated trees in the seedling class, (T301, T421), and on 1 plot (T421) mortality dominated the trees in the sapling class.

Table 2. Evidence of recent harvest or disease affecting plots. Information taken from observations made in plot notes and sketches. Plots without notes regarding recent harvest or disease are not included in the table.

Plot	Evidence of recent harvest or disease
AUR1	Pre-commercial thinning, skid trails on plot
BED1	Many *Fagus grandifolia* broken up as a result of beech bark disease
CEN1	Many old skid roads
CHE1	Cut-over area
KOS2	Some skid trails
LIN1	Young stand
NOR1	Skid trails
OSB1	Pre-commercial thinning
SPR1	Some harvesting in area
T161	Pre-commercial thinning
T221	Recent thinning; patches of spruce and fir in seedling/sapling hardwood matrix
T311	Some skid trails through plot
T341	Pre-commercial thinning
T421	Clear cut up-slope; skid trail through plot; nonhost species also seem to be declining
TOP1	Recent thinning

Basal area, dbh and density were calculated for each plot by species (Table A. 2). These calculations included all live trees that were at least 12.6 cm dbh and all standing dead fir and standing fir snags. The species richness of live trees on plots ranged from 2 to 9—this is a simple count of the number of species in a given area. Basal area of live fir ranged from 1.7 to 15.7 m^2/ha; average diameter from 14.2 to 28.9 cm; and densities from 62 to 704 stems/ha. Species selected for nonhost cores included red spruce (*Picea rubens*) on 16 plots, white spruce (*Picea glauca*) on 4 plots, eastern white pine (*Pinus strobus*) on 3 plots, sugar maple (*Acer saccharum*) on 2 plots, red and white spruce on 1 plot, black spruce (*Picea mariana*) on 1 plot, northern white cedar (*Thuja occidentalis*) on 1 plot, and eastern hemlock (*Tsuga canadensis*) on 1 plot.

Tree-ring Chronologies

Tree-ring series were separated by tree group and by plot for analysis purposes in COFECHA, ARSTAN, and growth trend calculations. If the less affected fir group had fewer than 5 trees on a plot, the group was excluded from analyses. Average age of less affected fir ranged from 22 to 69 years (Table 3); more affected from 26 to 74 years (Table 4), and nonhost from 24 to 120 years (Table 5). Mean sensitivity was generally low to moderate with values ranging from 0.16 to 0.25 in less affected fir, from 0.16 to 0.28 in more affected fir and from 0.19 to 0.35 in nonhost trees. Values of less than 0.2 indicate complacent series, while those between 0.2 and 0.3 indicate moderately sensitive series, and above 0.3, sensitive series (Grissino-Mayer 2001). All three groups had several plots that fell below the suggested threshold of age for successful cross-dating (Pilcher 1990). However there were recognizable patterns in the ring widths, and these ages reflect the range of ages of BWA-affected stands in the study area.

Table 3. Summary statistics for less affected fir raw ring-width chronologies. N is the number of cores used in COFECHA. Segment length was set at 30 years; the critical value for **intercorrelation** at the 99% confidence level is 0.4226; plots not meeting this criterion are indicated in *italics*. **Master Length** is the length of the chronology developed by COFECHA, **Mean length**, the mean length in years of the cores. **Age** was estimated from all cores with a pith or whose age to pith could be estimated; **n** indicates the total number of cores used in the age calculation, **n_est** is the number of cores whose age had to be estimated. **Max Age** is the age at dbh of the oldest tree used in the age calculation. Max age differs from master length because some chronologies included dead trees and some cores had rings to pith added. **DBH** is the average diameter at breast height of the trees whose cores were used to develop the age estimate.

Plot	N	Inter-correlation	Sensitivity	Mean ring-width ± se (mm)	Master length (yr)	Mean length (yr)	Age ± se (n, n_est)	Max Age	DBH ±se (n) (cm)
AUR1	14	0.515	0.19	2.57 ± 0.23	36	26.9	28.3 ± 1.3 (13, 6)	36	15.3 ± 0.6 (13)
CEN1	12	*0.348*	0.20	2.23 ± 0.20	50	30.3	33.2 ± 3.5 (11, 8)	66	14.9 ± 0.6 (11)
CHE1	9	*0.406*	0.23	1.90 ± 0.34	100	44.2	47.6 ± 8.3 (8, 7)	102	16.7 ± 0.8 (8)
GRE1	11	0.555	0.24	1.25 ± 0.20	124	64.5	67.4 ± 7.0 (10, 8)	124	18.9 ± 0.7 (10)
KOS2	9	*0.421*	0.19	1.58 ± 0.20	57	51.1	51.9 ± 2.8 (9, 7)	59	18.0 ± 1.0 (9)
LIN1	5	*0.350*	0.17	3.35 ± 0.59	32	30.2	31.4 ± 0.8 (5, 3)	34	23.8 ± 3.7 (5)
NOR1	13	0.461	0.19	2.35 ± 0.25	42	27.5	28.7 ± 1.9 (11, 6)	44	15.4 ± 0.5 (11)
OSB1	5	*-0.020*	0.25	3.23 ± 0.45	43	20.2	24.3 ± 7.3 (4, 3)	46	14.2 ± 1.0 (4)
SPR1	10	0.532	0.20	1.67 ± 0.17	72	45.1	49.7 ± 3.7 (9, 7)	72	17.2 ± 1.1 (9)
T161	9	*0.407*	0.23	3.85 ± 0.49	34	20.6	22.0 ± 2.5 (9, 7)	38	18.1 ± 1.2 (9)
T221	11	*0.380*	0.18	3.47 ± 0.28	33	26.4	27.8 ± 1.0 (11, 7)	36	21.2 ± 1.3 (11)
T341	14	0.556	0.19	1.92 ± 0.20	40	32.6	36.1 ± 0.8 (11, 5)	40	15.7 ± 0.8 (11)
T362	9	*0.413*	0.23	1.13 ± 0.18	71	64.7	69.0 ± 1.5 (9, 7)	77	17.6 ± 1.3 (9)
T411	6	0.561	0.16	1.24 ± 0.27	48	44.2	47.3 ± 1.4 (6, 5)	52	13.6 ± 0.4 (6)
TOP1	14	0.519	0.19	1.86 ± 0.20	46	37.2	37.8 ± 1.1 (14, 8)	45	15.3 ± 0.4 (14)

Table 4. Summary statistics for more affected fir raw ring-width chronologies. See Table 3 for description of column headings.

Plot	N	Inter-correlation	Mean Sensitivity	Mean ring-width ± se (mm)	Master length (yr)	Mean length (yr)	Age ± se (n, n_est)	Max Age	DBH ± se (n) (cm)
AUR1	14	0.589	0.21	2.52 ± 0.29	44	32.8	35.9 ± 1.3 (11, 8)	45	19.6 ± 1.2 (11)
BED1	13	0.488	0.20	1.38 ± 0.19	80	66.5	70.5 ± 3.6 (12, 8)	82	22.1 ± 1.2 (12)
BUR1	13	0.496	0.22	2.01 ± 0.27	76	52.2	54.7 ± 2.1 (12, 6)	75	24.4 ± 1.3 (12)
CEN1	13	*0.382*	0.19	1.91 ± 0.21	73	50.2	60.4 ± 5.5 (9, 9)	82	23.0 ± 0.9 (9)
CHE1	12	0.460	0.19	1.98 ± 0.22	62	45.7	50.3 ± 3.3 (11, 8)	69	22.6 ± 1.1 (11)
GRE1	14	0.602	0.22	1.19 ± 0.17	69	58.6	61.8 ± 1.7 (13, 9)	72	17.3 ± 1.0 (13)
KOS1	13	0.439	0.25	1.88 ± 0.26	60	52.5	56.9 ± 0.8 (10, 6)	62	23.7 ± 1.9 (10)
KOS2	14	0.447	0.19	1.65 ± 0.15	63	55.2	55.7 ± 1.0 (14, 9)	62	20.4 ± 0.9 (14)
LIN1	14	0.478	0.19	2.83 ± 0.33	60	41.7	48.2 ± 3.3 (11, 8)	59	28.0 ± 1.9 (11)
NOR1	14	0.564	0.22	2.50 ± 0.29	47	31.8	34.7 ± 2.6 (11, 5)	47	19.4 ± 1.1 (11)
OSB1	13	0.515	0.25	1.87 ± 0.30	56	43.7	46.1 ± 3.2 (12, 7)	56	18.8 ± 1.0 (12)
SPR1	13	0.516	0.21	1.73 ± 0.23	54	47.0	51.2 ± 1.8 (10, 7)	62	19.5 ± 1.0 (10)
T161	12	0.450	0.25	3.43 ± 0.50	46	24.3	25.7 ± 2.6 (12, 8)	46	19.6 ± 1.4 (12)
T221	12	0.442	0.18	3.30 ± 0.28	30	26.8	28.5 ± 0.3 (11, 7)	30	20.2 ± 1.1 (11)
T251	13	0.443	0.16	1.85 ± 0.21	50	37.3	42.2 ± 2.3 (10, 10)	52	16.9 ± 1.0 (10)
T281	12	*0.297*	0.21	2.83 ± 0.34	45	34.3	38.0 ± 1.6 (7, 7)	46	24.0 ± 1.8 (7)
T291	13	0.454	0.18	1.42 ± 0.18	78	65.8	70.4 ± 2.3 (11, 9)	81	22.7 ± 0.7 (11)
T301	13	*0.346*	0.19	1.58 ± 0.19	69	57.8	59.7 ± 2.7 (11, 7)	73	20.0 ± 0.9 (11)
T311	14	0.475	0.21	2.45 ± 0.31	54	33.8	40.4 ± 3.0 (9, 6)	54	19.1 ± 1.2 (9)
T321	13	0.451	0.21	1.16 ± 0.16	88	63.3	64.2 ± 4.5 (11, 6)	87	16.2 ± 0.5 (11)
T341	14	0.620	0.21	1.98 ± 0.29	44	35.2	38.7 ± 0.8 (10, 5)	45	16.8 ± 0.8 (10)
T351	10	*0.360*	0.28	2.13 ± 0.32	61	46.8	55.3 ± 2.8 (7, 6)	65	24.3 ± 1.5 (7)
T362	14	0.452	0.20	1.24 ± 0.16	82	64.2	66.2 ± 1.6 (14, 10)	80	17.6 ± 0.7 (14)
T391	15	*0.397*	0.26	1.93 ± 0.26	79	54.6	62.8 ± 2.6 (12, 11)	83	25.7 ± 2.1 (12)
T411	13	0.468	0.18	1.36 ± 0.21	54	48.6	51.7 ± 0.5 (12, 8)	57	17.4 ± 1.0 (12)
T421	12	0.545	0.22	2.35 ± 0.37	62	52.8	57.6 ± 2.0 (10, 8)	71	28.2 ± 1.6 (10)
T431	14	0.521	0.21	0.97 ± 0.11	78	69.9	74.4 ± 1.7 (12, 9)	79	18.3 ± 0.7 (12)
TOP1	12	0.464	0.20	1.83 ± 0.21	54	44.7	45.5 ± 1.2 (12, 8)	53	18.3 ± 0.9 (12)
TOP2	12	0.513	0.21	2.08 ± 0.27	77	58.6	65.0 ± 2.2 (9, 7)	81	27.6 ± 1.2 (9)

Table 5. Summary statistics for nonhost raw ring-width chronologies. See Table 3 for description of column headings.

Plot	Nonhost species	N	Inter-correlation	Sensitivity	Mean ring-width ± se (mm)	Master length (yr)	Mean length (yr)	Age ± se (n, n_est)	Max Age	DBH ± se(n) (cm)
AUR1	*Pinus strobus*	14	0.590	0.19	4.68 ± 0.48	37	28.1	33.1 ± 1.4 (13, 13)	40	31.5 ± 2.1 (13)
BED1	*Picea rubens*	12	0.490	0.21	1.91 ± 0.18	78	51.9	59.0 ± 4.2 (12, 10)	84	23.2 ± 1.4 (12)
BUR1	*Acer saccharum*	11	*0.333*	0.35	0.79 ± 0.19	132	111.3	120.3 ± 4.9 (11, 9)	147	21.8 ± 1.0 (11)
CEN1	*Picea spp.*	12	*0.346*	0.21	2.43 ± 0.26	81	42.6	45.2 ± 3.5 (12, 11)	81	24.1 ± 1.6 (12)
CHE1	*Picea rubens*	12	*0.362*	0.19	1.88 ± 0.20	52	45.6	48.3 ± 1.3 (10, 9)	54	20.2 ± 1.2 (10)
GRE1	*Picea rubens*	12	*0.422*	0.21	1.40 ± 0.15	122	88.3	91.9 ± 8.1 (12, 10)	128	26.8 ± 2.0 (12)
KOS1	*Acer saccharum*	13	*0.319*	0.30	1.43 ± 0.29	59	51.7	54.2 ± 0.8 (13, 10)	59	17.4 ± 1.1 (13)
KOS2	*Tsuga canadensis*	13	0.441	0.24	1.34 ± 0.16	118	87.1	90.3 ± 6.1 (12, 11)	122	29.1 ± 1.4 (12)
LIN1	*Picea glauca*	11	0.442	0.23	2.82 ± 0.40	61	49.9	52.1 ± 2.9 (11, 10)	68	30.9 ± 1.4 (11)
NOR1	*Pinus strobus*	12	0.496	0.20	3.68 ± 0.40	28	23.3	24.3 ± 0.4 (12, 6)	28	19.5 ± 1.3 (12)
OSB1	*Picea rubens*	12	0.603	0.22	2.07 ± 0.24	56	44.0	46.0 ± 4.4 (12, 8)	58	19.0 ± 0.9 (12)
SPR1	*Thuja occidentalis*	13	0.490	0.20	1.34 ± 0.16	119	85.3	98.0 ± 8.2 (8, 8)	123	30.6 ± 2.9 (8)
T161	*Picea rubens*	12	0.435	0.19	3.16 ± 0.27	29	21.5	23.8 ± 1.6 (11, 8)	32	16.2 ± 0.7 (11)
T221	*Picea rubens*	13	0.473	0.21	2.09 ± 0.22	60	45.6	47.2 ± 3.5 (13, 9)	61	21.4 ± 1.3 (13)
T251	*Picea rubens*	13	*0.374*	0.20	1.44 ± 0.15	107	76.0	79.7 ± 8.3 (13, 11)	110	24.0 ± 2.1 (13)
T281	*Picea rubens*	12	0.531	0.22	2.14 ± 0.29	135	59.9	62.1 ± 8.6 (11, 7)	134	27.4 ± 2.6 (11)
T291	*Picea rubens*	12	0.524	0.20	1.38 ± 0.20	138	97.6	104.3 ± 7.3 (12, 12)	143	29.2 ± 1.5 (12)
T301	*Picea rubens*	12	0.449	0.21	1.42 ± 0.21	159	81.1	87.5 ± 13.3 (11, 8)	163	24.3 ± 1.8 (11)
T311	*Picea rubens*	14	*0.386*	0.23	1.32 ± 0.19	155	84.6	90.9 ± 10.9 (14, 13)	156	23.5 ± 1.0 (14)
T321	*Picea rubens*	12	0.461	0.22	1.19 ± 0.17	161	85.3	87.7 ± 10.5 (12, 7)	165	21.4 ± 1.4 (12)
T341	*Picea glauca*	12	0.587	0.22	2.34 ± 0.29	39	33.1	34.8 ± 0.8 (12, 9)	39	17.6 ± 0.9 (12)
T351	*Picea rubens*	12	0.454	0.27	1.35 ± 0.21	130	94.4	97.6 ± 7.7 (12, 8)	130	26.8 ± 1.4 (12)
T362	*Picea rubens*	12	0.471	0.20	1.58 ± 0.20	131	78.5	82.8 ± 7.0 (12, 10)	131	27.8 ± 2.0 (12)
T391	*Picea glauca*	12	*0.410*	0.19	1.83 ± 0.23	79	60.3	65.9 ± 3.6 (11, 11)	84	26.2 ± 1.5 (11)
T411	*Picea mariana*	12	0.520	0.21	1.56 ± 0.26	55	49.5	52.5 ± 0.8 (12, 12)	57	19.1 ± 1.2 (12)
T421	*Picea glauca*	12	0.548	0.23	2.71 ± 0.52	48	43.9	46.3 ± 0.5 (12, 11)	49	28.1 ± 0.8 (12)
T431	*Picea rubens*	13	0.598	0.20	1.26 ± 0.15	96	73.6	78.3 ± 2.1 (12, 9)	99	23.3 ± 1.6 (12)
TOP1	*Pinus strobus*	12	0.589	0.26	3.32 ± 0.47	55	46.0	49.1 ± 1.6 (12, 11)	55	34.5 ± 1.8 (12)
TOP2	*Picea rubens*	13	0.586	0.24	1.26 ± 0.20	138	110.2	113.9 ± 9.6 (12, 9)	150	29.3 ± 1.2 (12)

Growth of more affected fir was not significantly less than less affected fir in a regionally significant (P<0.1) manner (See APPENDIX B for full results of mean comparisons and sign tests). Comparison of more affected fir and nonhost growth trends revealed that beginning in 1998 and continuing for 4 years (after which the sample size dropped to 6) at least 20 of the plots had more affected fir with reduced growth trends compared to the nonhost (Table 6, Figure 3); this is also reflected in plots of the standardized chronologies created in ARSTAN (APPENDIX C). This divergence was not random across the study area as indicated by the significant (P<0.1) sign test. It is the only period when the more affected fir growth trends fell below nonhost growth trends in a regionally significant manner for more than a year.

Table 6. Comparison between more affected fir and non-host growth trends. N fir<nh is the number of plots where the growth trend of the more affected fir was significantly less than that of the nonhost. **Total** is the total of number of plots included in analysis. **Sign test P-value** is the probability that this was a random event.

Year	N fir<nh	Total	Sign test P-value
1998	22	29	0.005
1999	20	28	0.019
2000	20	29	0.032
2001	21	28	0.007

In development of the chronology of rotholz occurrence, false presence of rotholz in the cores could have been recorded. This is because of the similarity of rotholz to compression wood; it was not possible to positively determine that rotholz was being examined. However, cores were taken on trees at least 12.6 cm diameter and compression wood would be unexpected in these specimens, especially in the outer rings. Rotholz occurrence is scattered such that an unknown number of cores failed to detect rotholz in the fir. Therefore, the values presented underestimate the total number of trees with rotholz. However, because of the random nature of the sampling, year to year variation in the proportion of trees with rotholz should reflect the year to year variation in the occurrence of BWA on stems of the trees.

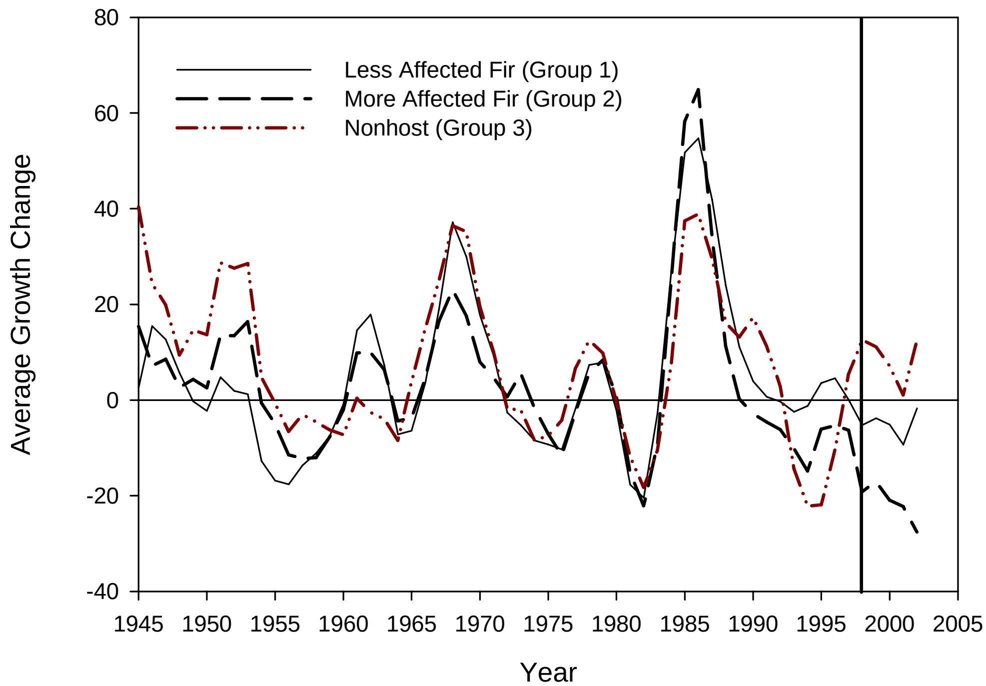


Figure 3. Growth trends by tree group averaged over all plots. Note, analysis was conducted by plot and data are presented in aggregate for clarity of presentation. Values below zero are periods of decreasing growth; values above zero indicate increasing growth. Solid vertical line is at 1998; the year in which more affected fir began to have significantly reduced growth trends in comparison to the nonhost.

The percent of cores ever having shown rotholz reached a maximum of 42%. 2001 had the most cores showing rotholz with approximately 23% affected. As the fir aged, there was a gradual buildup of rotholz (Figure 4, APPENDIX D). Apparently most stem infestations start on trees that are 12 to 28 years at DBH. A sharp increase in the percent of cores with rotholz is coincident with the termination of the spruce budworm outbreak in the mid 1980's. BWA had infested fir in the region prior to the spruce budworm outbreak (Irland *et al.* 1988), and the buildup could indicate adelgid population response to the rebuilding of a vigorous, nutritious food source after a period of foliage reduction and radial growth suppression by budworm defoliation.

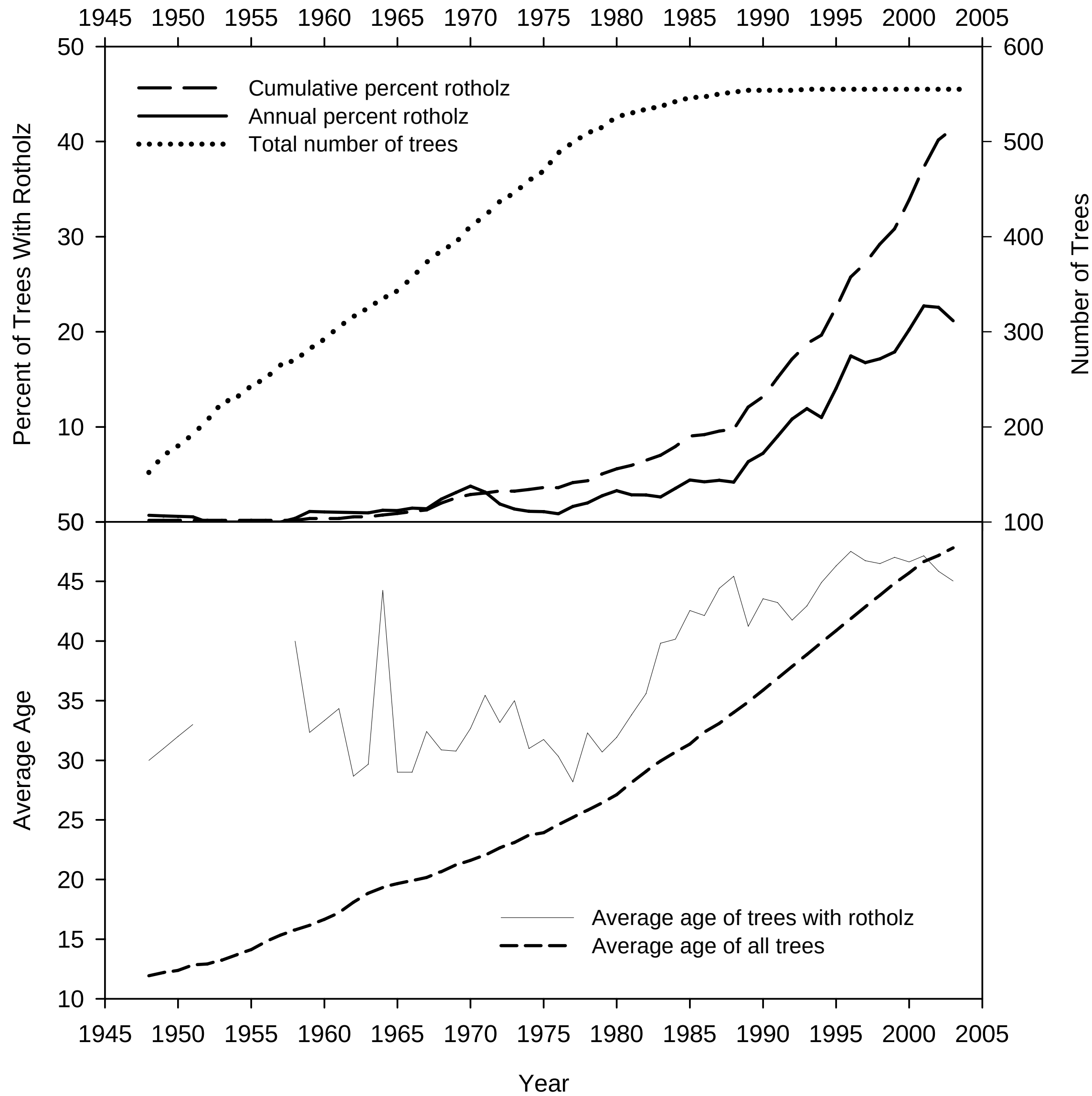


Figure 4. Percent rotholz and age of fir. Cumulative percent rotholz and percent rotholz by year in all measured fir are indicated in the upper pane. The top line shows the number of trees. Data shown are for period common to all 29 plots (from the first year rotholz was observed to 2003, the year of the last full ring for most cores). The lower pane shows the age of trees with rotholz by year and the average age of fir. Data used to create the lower pane included only trees with a pith or whose age to pith could be estimated.

Tree-ring and Climate Series

The two measures of available moisture, PDI and standardized precipitation, track each other well; with recovery from drought conditions indicated by PDI sometimes lagging precipitation increases (Figure 5). These measures indicate a significant drought in the study area from 2001 through 2002. This drought is thoroughly documented by Lombard (2004). Similar periods of droughts indicated by PDI occur from 1956 to 1957 and 1965 to 1966; additionally the period from 1939 to 1950 generally had below normal moisture with extreme lows in available moisture occurring from 1941 to 1942 and from 1948 to 1950. In most species on most plots these periods coincide with brief periods of growth reduction, followed by growth recovery (Figure C. 1). It may be too soon after the drought of 2001 to 2002 to see a recovery in the standardized chronologies; however an increase in the standardized ring-width occurred after 2002 more often in the less affected fir group and nonhost group than in the more affected fir group (APPENDIX C).

More severe growth reduction in more affected fir relative to the nonhost preceded the drought, beginning region-wide in 1998. However, fir mortality as indicated by the estimated last year of growth for recently dead trees appeared to coincide with the drought. Mortality peaked in 2002 (Table 7). Finding fewer trees that died prior to 2000 could be a result of deterioration of the sapwood; adelgid damaged fir begins to show advanced sap rot 3 years after death (Hudak 1976). Advanced sap rot could result in loss of bark and exclusion of these trees from the sample.

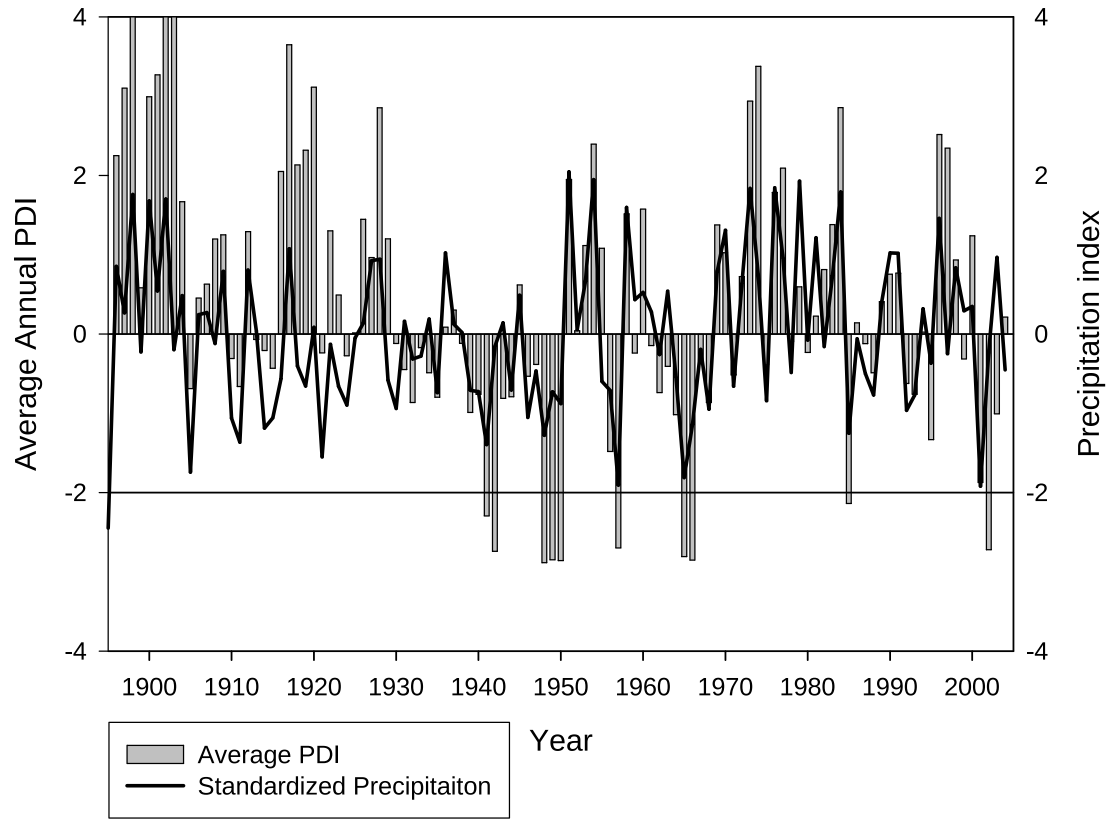


Figure 5. Average annual palmer drought severity index (PDI) and standardized precipitation. PDI values are for Maine region 2; 1895 through 2004. PDI values above 1.99 indicate moist years, below -1.99, dry. Values between -2 and -2.99 indicate moderate drought, between -3 and -3.99, severe drought, and -4 and below extreme drought. For clarity of presentation, standardized precipitation values presented in this figure were averaged across all plots. Analysis was carried out by plot. Yearly precipitation totals were estimated for each plot from Oregon State University's Spatial Climate Analysis Service (Spatial Climate Analysis Service 2005). Precipitation totals were standardized for each plot based on number of standard deviations the annual sum was from the 110 year average. For both values the year was averaged from November of the previous year to October of the current year.

Table 7. Year of outer ring formation in recently dead fir. This was only estimated for trees whose cores were selected for analysis. All recently dead trees had intact bark and outer rings.

	Year								Total by
Plot	**2004**	**2003**	**2002**	**2001**	**2000**	**1999**	**1998**	**1997**	**plot**
AUR1	-	-	1	-	-	-	-	-	1
BED1	-	-	-	1	-	-	-	-	1
BUR1	-	1	2	-	-	-	-	-	3
CEN1	-	-	-	-	-	1	-	-	1
CHE1	-	-	-	-	-	-	-	-	0
GRE1	-	1	1	1	-	-	-	-	3
KOS1	-	2	3	-	-	-	-	-	5
KOS2	-	-	-	-	-	1	-	-	1
LIN1	-	-	1	2	-	-	-	-	3
NOR1	-	1	-	-	-	-	-	-	1
OSB1	-	1	1	-	-	-	-	-	2
SPR1	-	-	-	-	-	-	-	-	0
T161	-	-	-	-	-	-	-	-	0
T221	-	-	-	-	-	-	-	-	0
T251	-	1	2	1	-	-	-	-	4
T281	-	1	2	1	2	-	-	-	6
T291	-	-	-	-	1	-	-	-	1
T301	-	2	3	1	-	-	-	-	6
T311	-	-	-	1	-	-	-	-	1
T321	-	-	-	-	-	-	-	1	1
T341	-	-	-	-	-	-	-	-	0
T351	-	1	-	-	-	-	-	-	1
T362	-	1	1	1	-	1	-	-	4
T391	-	-	-	2	-	1	-	-	3
T411	-	-	2	-	-	-	-	-	2
T421	-	-	2	4	-	-	-	-	6
T431	-	-	1	-	-	-	-	-	1
TOP1	1	1	1	-	-	-	-	-	3
TOP2	-	-	-	-	-	-	-	-	0
Total by year	1	13	23[a]	15[a]	3	4	0	1	60

[a] 2001 and 2002 were identified as years of severe drought in Maine (Lombard 2004).

Temperature records gathered from a north-south transect of weather stations indicate that except at the northern-most station there was a universal decline in the frequency of occurrence of lethal temperature events since the mid-1930's. This is evident in frequency of temperatures below the freezing point of BWA (-34° C) (Figure 6), and the frequency of temperatures that cause high levels of mortality (-30° C) (Figure 7). Also demonstrated is a more recent pattern of relatively mild winters within the study area in the late 1990's. This is reflected in the scarcity of days below -20.5° C (Figure 8); the threshold at which mortality begins in diapausing neosistentes (Clark *et al.* 1971). The lack of winter temperatures that cause significant mortality would have allowed a gradual buildup of adelgid populations with the presence of a healthy, abundant food source. This is reflected in the buildup of rotholz. We expected to see a relationship between fluctuations in winter temperatures and year to year presence of rotholz in the cores. No consistent pattern was detected; perhaps in older stands with a longer record of infestation such a pattern would have emerged.

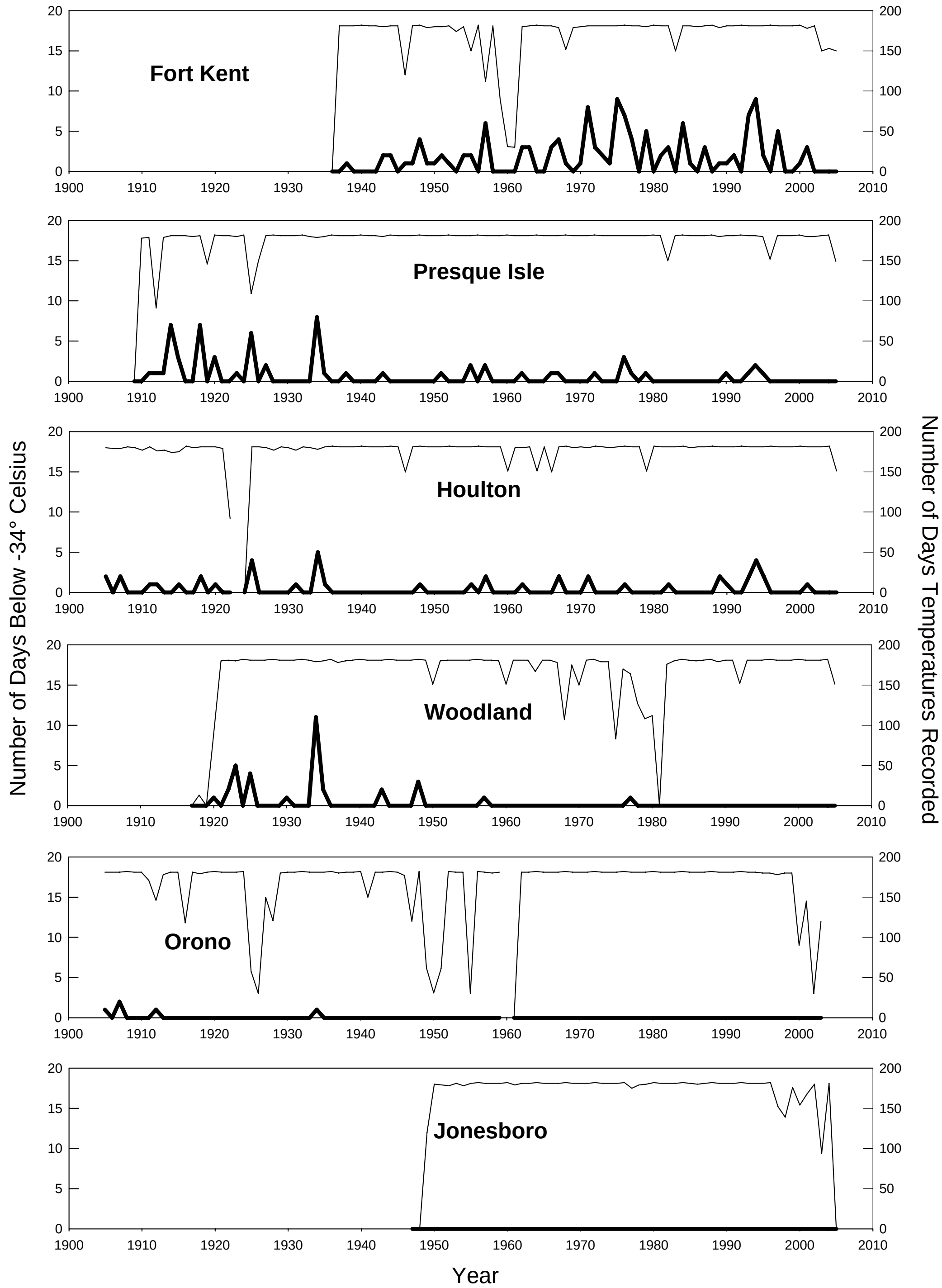


Figure 6. Number of days (Nov.-Apr.) with minimum temperatures at or below -34º C (-30º F) (heavy line). Number of days that information was recorded is indicated by the light line**.** Weather stations arranged from north to south.

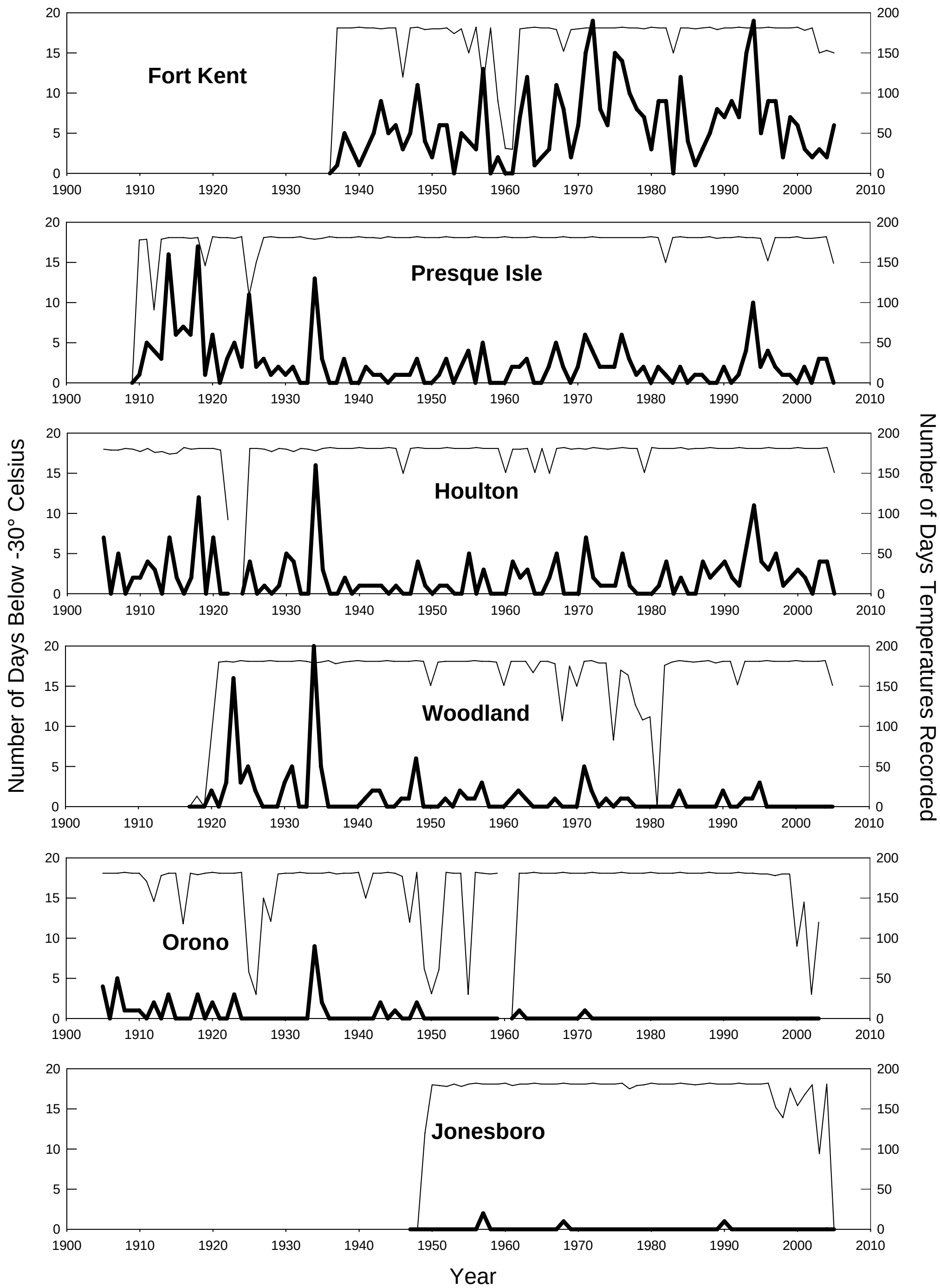


Figure 7. Number of days (Nov.-Apr.) with minimum temperature at or below -30º C (-22º F) (heavy line). Number of days that information was recorded is indicated by the light line**.** Weather stations arranged from north to south.

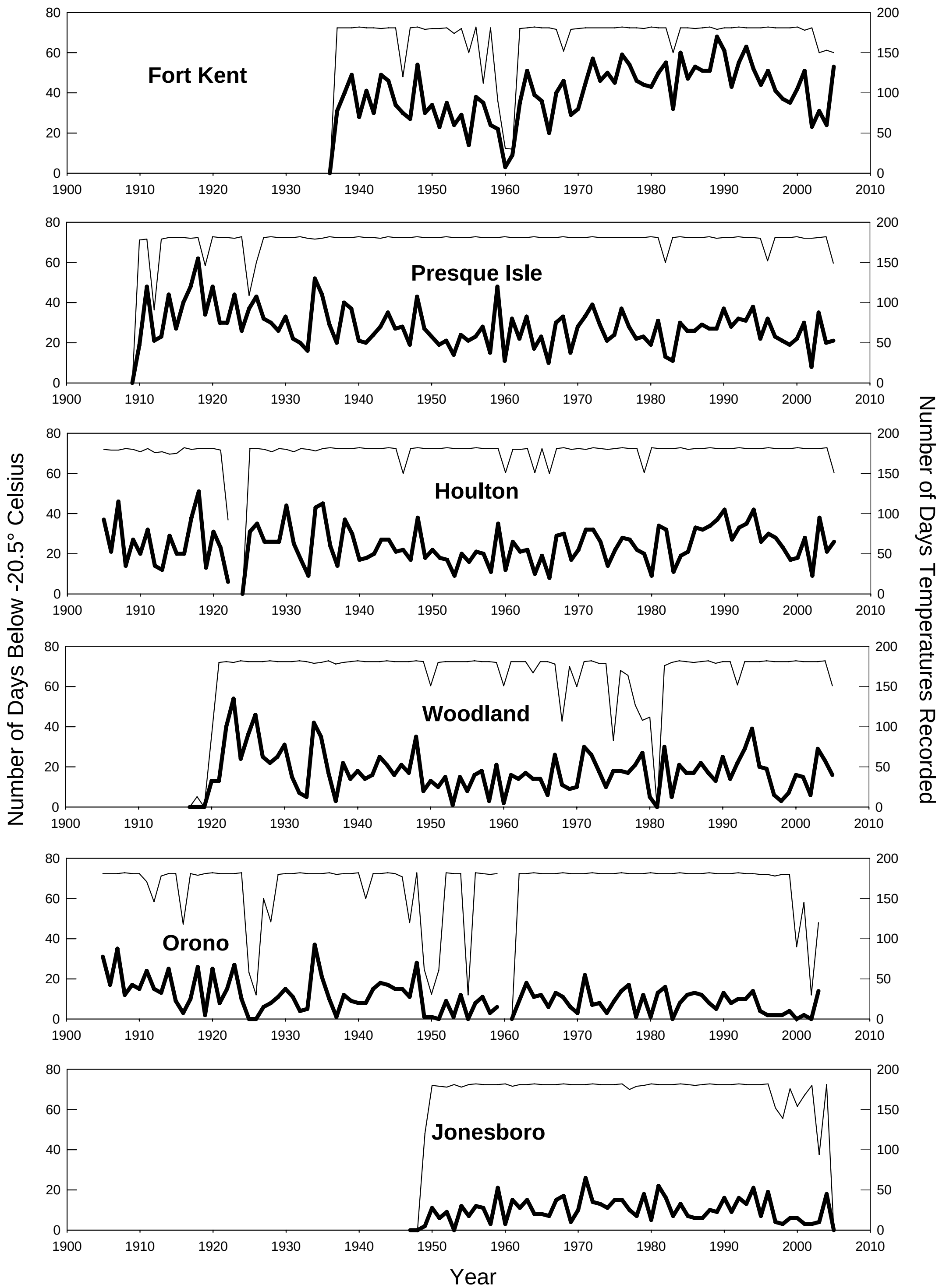


Figure 8. Number of days (Nov.-Apr.) with minimum temperature at or below -20.5º C (-5º F) (heavy line). Number of days that information was recorded is indicated by the light line**.** Weather stations arranged from north to south.

Damage, Plot, and Tree Relationships

At the plot level there were several significant correlations among and between plot variables (Table A. 4) and damage variables (Table A. 5). Significant Bartlet X^2 test statistics ($P<0.001$) indicate that these P-values are reasonable (Wilkinson *et al.*2004); however they have not been adjusted for family level interpretation.

Important correlations among plot variables include negative correlations between average fir age with percent fir ($r = -0.62$, $P<0.001$), age with basal area of fir ($r = -0.37$, $P=0.046$) and average height with percent fir ($r = -0.54$, $P = 0.002$) (Table 8). Stands in the study with the most fir tended to contain the youngest, shortest trees; trees which in general are less susceptible to drought-stress and thus less vulnerable to severe damage from BWA (Page 1975).

Table 8. Correlations of tree variables and latitude among plots. Age, height and dbh were averaged by plot. Significant correlations ($P \leq 0.1$) indicated in **bold**. P-value indicated in parentheses. Fir dbh was log transformed prior to analysis. Bartlett X^2 statistic for correlation matrix: 232 df=36 P< 0.001

	Fir Age	Fir Height (m)	Fir dbh (cm)	Total BA (m^2/ha)	Fir BA (m^2/ha)	Fir (% BA)	Total Density (stems/ha)	Live and Dead Fir Density (stems/ha)
Fir Height (m)	**0.66** (<0.001)							
Ln Fir DBH	0.22 (0.243)	**0.69** (<0.001)						
Total BA (m^2/ha)	**0.59** (0.001)	**0.64** (<0.001)	0.25 (0.197)					
Fir BA (m^2/ha)	**-0.37** (0.046)	-0.21 (0.263)	0.00 (0.991)	-0.11 (0.579)				
Fir (% BA)	**-0.62** (<0.001)	**-0.54** (0.002)	-0.20 (0.303)	**-0.67** (<0.001)	**0.74** (<0.001)			
Total Density (stems/ha)	**0.40** (0.033)	0.25 (0.200)	-0.24 (0.210)	**0.68** (<0.001)	0.07 (0.726)	**-0.36** (0.057)		
Live and Dead Fir Density (stems/ha)	**-0.41** (0.030)	**-0.37** (0.046)	-0.30 (0.120)	-0.22 (0.235)	**0.86** (<0.001)	**0.75** (<0.001)	0.11 (0.554)	
Latitude Rank	**0.46** (0.012)	**0.35** (0.064)	0.18 (0.341)	0.04 (0.832)	0.07 (0.705)	0.02 (0.912)	0.01 (0.971)	-0.06 (0.763)

In general, correlations among damage measures were weaker than correlations among plot variables (Table 9). The damage index had a strong positive correlation with the rank of percent dead fir (r=0.87, P<0.001), the percent of fir basal area in the more affected class (r = 0.53, P =0.003) and the dieback rank (r=0.60, P=0.001). Two indicators of trunk infestation, the percent of live fir stems with adelgid and the percent of cores exhibiting evidence of rotholz, were positively correlated with the damage index (r = 0.35, P = 0.066 and r = 0.49, P = 0.007) and with each other (r = 0.73, P<0.001). The damage index reflects the severity of the expression of injury in the crown, and the trunk phase and rotholz are indicators of stem injury; it is logical that these would be positively correlated. The strong correlation between the damage index and rank of percent dieback is expected because BWA damage rating is a rating of dieback. It takes into account more dieback in the crown than the Forest Service's (2003) traditional measure, as the damage from adelgid causes needle and twig loss throughout the crown.

Table 9. Correlations of damage variables among plots. Damage index, crown density, dieback, transparency, and live crown ratio averaged by plot. Significant correlations (P≤0.1) indicated in **bold**. P-value indicated in parentheses. Bartlett X^2 statistic for correlation matrix: 125 df=36 P= 0.000

	Damage Index	**Group 2 (% BA)**	**Trunk Phase (% n)**	**Cores with Rotholz (%)**	**Dead Rank (% BA)**	**Crown Density**	**Dieback Rank**	**Trans-parency**
Group 2 (% BA)	**0.53** (0.003)							
Trunk Phase (% n)	**0.35** (0.066)	0.29 (0.125)						
Cores with Rotholz (%)	**0.49** (0.007)	0.23 (0.232)	**0.73** (<0.001)					
Dead Rank (% BA)	**0.87** (<0.001)	**0.44** (0.017)	0.24 (0.216)	0.30 (0.111)				
Crown Density	-0.25 (0.193)	0.00 (0.996)	-0.30 (0.114)	-0.14 (0.455)	-0.20 (0.304)			
Dieback Rank	**0.60** (0.001)	**0.70** (<0.001)	0.26 (0.173)	0.27 (0.159)	**0.38** (0.041)	-0.29 (0.122)		
Transparency	**0.41** (0.028)	**0.41** (0.029)	**0.51** (0.004)	**0.52** (0.004)	0.26 (0.167)	-0.11 (0.565)	**0.44** (0.016)	
Live Crown Ratio	**-0.40** (0.032)	-0.3 (0.115)	-0.05 (0.787)	-0.03 (0.867)	**-0.45** (0.016)	0.12 (0.543)	-0.22 (0.262)	0.05 (0.788)

As the percent of trees with trunk phase on a plot increased, the average transparency increased (r = 0.51, P = 0.004). Additionally, the percent of cores on the plot with evidence of rotholz was positively correlated with transparency (r = 0.52, P = 0.004). These relationships could reflect reduction in needles as a result of drought-impacts from the trunk attack.

Several significant correlations of interest occurred between the damage and plot variables (Table 10). The damage index was positively correlated with average height (r = 0.38, P = 0.043) and the natural log of dbh (r =0.42, P=0.022). The percent of fir basal area in the more affected tree group (Group 2) had a similar relationship with fir age (r = 0.44, P = 0.018), height (r = 0.42, P = 0.024) and diameter (r = 0.49, P = 0.008). This was expected as infestations tend to start on larger diameter, taller trees (Balch 1952, Greenbank 1970); and injury may become more pronounced as trees grow larger and are more prone to water stress (Page 1975, Hain 1988).

There were negative correlations between the damage index and basal area of fir (r = -0.57, P=0.001), percent fir (r = -0.46 P=0.013), and live and recent dead fir density (r = -0.43, P<0.018). In his risk assessment for damage to balsam fir in Newfoundland Page (1975) had suggested that more severe damage would occur in stands with a higher percent fir. The discrepancy in our findings may be a result of the fact that most of our plots with a higher percent fir were young and short compared to the plots with a lower percent fir (Table 8). The negative relationship of damage with fir density suggests that more widely spaced fir (fewer per hectare) suffer more severe damage than denser stands. This supports previous observations that damage is more severe in thinned than in un-thinned stands (Brower 1947, Greenbank 1970).

A weak positive relationship between occurrence of trunk phase and dbh (r = 0.32, P = 0.086) was found. A similar relationship was seen between occurrence of rotholz in the cores and dbh (r = 0.37, P = 0.051). The same trend was observed on the nearby Penobscot Experimental Forest in Bradley, Maine (Greenbank 1970).

Mean live crown ratio, which may be as much a descriptor of plot conditions as it is an indicator of damage, was negatively correlated with average age of fir (r = -0.77, P<0.001), average height (r = -0.74, P<0.001) and total basal area (r = -0.63, P<0.001). However, mean live crown ratio was positively correlated with percent fir (r = 0.68, P<0.001) and basal area of fir (r = 0.40, P = 0.032). The plots dominated by fir tended to have deeper crowns than those with less basal area in fir. These also tended to be younger plots with a lower total basal area.

Table 10. Correlations between tree variables and latitude (row) and damage (column) variables among plots. Age, height, dbh, damage, crown density, dieback, transparency and live crown ratio were averaged by plot. Significant correlations (P≤0.1) indicated in **bold**. P-value indicated in parentheses. Bartlett X^2 statistic for correlation matrix: 313 df=56 P <0.001 n=29

	Damage Index	**Group 2 (% BA)**	**Trunk Phase (% n)**	**Cores with Rotholz (%)**	**Dead Rank (% BA)**	**Crown Density**	**Dieback Rank**	**Trans-parency**	**Live Crown Ratio**
Fir Age	0.29 (0.127)	**0.44** (0.018)	0.19 (0.335)	0.04 (0.835)	0.28 (0.148)	-0.07 (0.709)	0.30 (0.108)	0.08 (0.691)	**-0.77** (<0.001)
Fir Height (m)	**0.38** (0.043)	**0.42** (0.024)	0.09 (0.655)	0.00 (0.997)	**0.32** (0.095)	0.00 (0.980)	0.17 (0.391)	-0.07 (0.705)	**-0.76** (<0.001)
Fir DBH (cm)	**0.42** (0.022)	**0.49** (0.008)	**0.32** (0.086)	**0.37** (0.051)	0.21 (0.280)	0.01 (0.965)	0.29 (0.132)	0.14 (0.472)	-0.25 (0.187)
Total BA (m^2/ha)	0.12 (0.535)	0.25 (0.185)	-0.05 (0.791)	-0.10 (0.619)	0.14 (0.454)	0.05 (0.783)	0.06 (0.762)	0.10 (0.597)	**-0.63** (<0.001)
Fir BA (m^2/ha)	**-0.57** (0.001)	-0.31 (0.105)	0.09 (0.633)	-0.02 (0.889)	**-0.64** (<0.001)	0.08 (0.682)	-0.30 (0.109)	-0.02 (0.914)	**0.39** (0.035)
Fir (% BA)	**-0.46** (0.013)	**-0.38** (0.044)	0.13 (0.498)	0.02 (0.900)	**-0.54** (0.003)	0.03 (0.873)	-0.24 (0.203)	-0.08 (0.673)	**0.67** (<0.001)
Total Density (stems/ha)	-0.21 (0.271)	-0.05 (0.801)	-0.24 (0.210)	-0.29 (0.130)	-0.13 (0.496)	0.26 (0.175)	-0.08 (0.670)	-0.13 (0.500)	**-0.42** (0.023)
Fir Density (stems/ha)	**-0.43** (0.018)	**-0.47** (0.010)	-0.04 (0.982)	-0.06 (0.768)	**-0.47** (0.010)	0.03 (0.882)	-0.27 (0.150)	-0.03 (0.887)	**0.37** (0.049)
Latitude Rank	-0.07 (0.711)	0.02 (0.912)	0.15 (0.431)	0.16 (0.428)	-0.08 (0.693)	0.11 (0.561)	-0.25 (0.196)	0.02 (0.906)	-0.25 (0.183)

It was expected that rank of latitude, which is closely related to climate zone, would be negatively correlated with damage severity. That is, from south to north one would expect a decrease in damage severity due to lower winter temperatures. However, there were no significant ($P<0.1$) correlations between damage indicators and latitude rank. This could have been influenced by a prolonged period of sub-lethal winter temperatures and/or the correlation of latitude rank with height ($r = 0.35$, $p=0.064$) and age ($r = 0.46$ $p = 0.012$).

The ANCOVA comparing damage severity between sites indicated that when age was taken into account, there were no significant differences in mean damage levels (Figure 9). Our findings indicate that site class may not impact the level of damage severity in the region of study once the adelgid has become established. This does not agree with a study in Newfoundland which found soil moisture (a factor closely tied to site in this study) was the best indicator of damage, with damage severity increasing as soil moisture decreased (Page 1975). Results from the current study may have been blurred by the discrepancies in stand histories and the focus on finding stands with at least 12 more affected fir trees or by the small sample size (29 sites) of our study compared to Page's (424 sites).

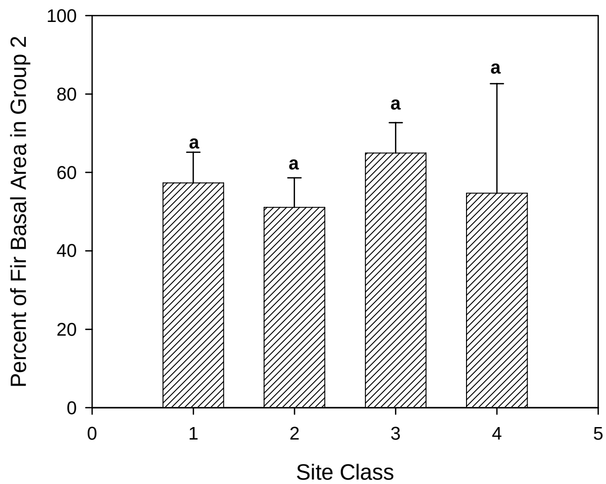


Figure 9. Mean damage severity by site class adjusted for age. Damage severity is measured by percent of live and recently dead fir basal area in more affected fir (Group 2). There was no significant difference (P>0.1) in damage severity across site classes when age was taken into account**.** Error bars reflect standard errors.

A two-sample t-test was used to examine damage at the tree level, as opposed to the plot level. This analysis included trees from both on and off plot. Fourteen plots had at least 5 fir in each damage group (more and less affected). From these 14, 5 had fir with larger diameters associated with more severe damage; 5 had taller fir coinciding with more severe damage and 3 had older trees coinciding with more severe damage (Table 11). The remaining means of these variables were not significantly different, or they could not be used because the data were not normally distributed. Previous investigations of BWA damage have found that larger diameter, taller trees with deeper crowns were more susceptible to damage (Balch 1952, Bakuzis and Hansen 1965, Johnson *et al.* 1963, Greenbank 1970). Results in this study are less clear; perhaps due to different definitions of damage severity and the relatively uniform-size and age of trees on each plot.

Table 11. Mean comparisons between more and less affected fir. Values in "Less" columns are for fir in the less affected fir group. Values in "More" columns are for fir in the more affected fir group. Results of two-sample t-test with P-value Bonferroni adjusted. Significantly different ($P \leq 0.1$) means indicated in **bold**. Variables that could not be made normal by natural log transformation are indicated in *italics*; means are presented for these variables, but not used in analysis. All means are reported in original units. **N** is the number of trees in a group for DBH, Height and Age. **Uncompacted live crown ratio** is not recorded for dead trees therefore; n for this variable is reported with the means.

	N		**DBH ± se (cm)**			**Height ± se (m)**			**Age ± se**			**Uncompacted Live Crown Ratio ± se (n)**		
Plot	Less	More	Less	More	P	Less	More	P	Less	More	P	Less	More	P
AUR1	13	11	**15.3 ± 0.6**	**19.6 ± 1.2**	0.026	11.6 ± 0.3	12.4 ± 0.4	0.501	**28.3 ± 1.3**	**35.9 ± 1.3**	0.002	72 ± 6 (13)	64 ± 5 (10)	1.000
CEN1	11	9	*14.9 ± 0.6*	*23.0 ± 0.9*	*N/A*	*12.1 ± 0.5*	*13.7 ± 0.6*	*N/A*	*33.2 ± 3.5*	*60.4 ± 5.5*	*N/A*	62 ± 5 (11)	61 ± 7 (8)	1.000
CHE1	8	11	**16.7 ± 0.8**	**22.6 ± 1.1**	0.002	**12.4 ± 0.6**	**14.9 ± 0.5**	0.030	47.6 ± 8.3	50.3 ± 3.3	1.000	64 ± 7 (8)	72 ± 6 (11)	1.000
GRE1	10	13	18.9 ± 0.7	17.3 ± 1.0	0.721	15.6 ± 0.4	15.8 ± 0.6	1.000	67.4 ± 7.0	61.8 ± 1.7	1.000	42 ± 4 (10)	44 ± 5 (9)	1.000
KOS2	9	14	18.0 ± 1.0	20.4 ± 0.9	0.393	14.0 ± 0.7	15.4 ± 0.5	0.418	*51.9 ± 2.8*	*55.7 ± 1.0*	N/A	53 ± 7 (9)	47 ± 3 (13)	1.000
LIN1	5	11	23.8 ± 3.7	28.0 ± 1.9	1.000	**14.9 ± 0.6**	**17.4 ± 0.3**	0.034	**31.4 ± 0.8**	**48.2 ± 3.3**	0.002	71 ± 8 (5)	67 ± 4 (9)	1.000
NOR1	11	11	**15.4 ± 0.5**	**19.4 ± 1.1**	0.017	11.7 ± 0.4	12.7 ± 0.5	0.417	28.7 ± 1.9	34.7 ± 2.6	0.292	54 ± 3 (11)	63 ± 4 (11)	*N/A*
SPR1	9	10	17.2 ± 1.1	19.5 ± 1.0	0.586	**13.2 ± 0.4**	**15.7 ± 0.5**	0.005	49.7 ± 3.7	51.2 ± 1.8	1.000	72 ± 5 (9)	58 ± 4 (10)	0.182
T161	9	12	18.1 ± 1.2	19.6 ± 1.4	1.000	10.4 ± 0.5	10.6 ± 0.5	1.000	22.0 ± 2.5	25.7 ± 2.6	1.000	91 ± 3 (9)	78 ± 3 (12)	1.000
T221	11	11	21.2 ± 1.3	20.2 ± 1.1	1.000	14.3 ± 0.6	14.2 ± 0.4	1.000	*27.8 ± 1.0*	*28.5 ± 0.3*	*N/A*	64 ± 6 (11)	60 ± 5 (11)	1.000
T341	11	10	15.7 ± 0.8	16.8 ± 0.8	1.000	12.2 ± 0.3	12.2 ± 0.3	1.000	36.1 ± 0.8	38.7 ± 0.8	0.134	62 ± 4 (11)	64 ± 4 (10)	1.000
T362	9	14	17.6 ± 1.3	17.6 ± 0.7	1.000	17.1 ± 0.5	16.9 ± 0.4	1.000	69.0 ± 1.5	66.2 ± 1.6	0.863	32 ± 3 (9)	32 ± 2 (10)	1.000
T411	6	12	**13.6 ± 0.4**	**17.4 ± 1.0**	0.016	**11.8 ± 0.7**	**14.4 ± 0.6**	0.067	*47.3 ± 1.4*	*51.7 ± 0.5*	*N/A*	67 ± 3 (14)	65 ± 6 (9)	0.423
TOP1	14	12	**15.3 ± 0.4**	**18.3 ± 0.9**	0.041	**10.7 ± 0.2**	**12.3 ± 0.4**	0.007	**37.8 ± 1.1**	**45.5 ± 1.2**	0.000	67 ± 3 (14)	65 ± 6 (9)	*N/A*

Conclusions

Adelgid populations have likely been allowed to build up as a result of a lack of extreme cold since 1935. The spruce budworm epidemic of the 1970's and early 1980's appears to have suppressed populations for a period, but rotholz records in this study suggest that populations have been increasing since the end of the epidemic. Beginning in 1998, trees showing more damage in general had growth trends that were lower than trees that were not directly affected by BWA (nonhost). This tendency observed in growth trend chronologies is also reflected in ARSTAN chronologies. Tree mortality seems to have been incited by the drought period peaking in 2002.

Based on our analysis of stands having BWA-related dieback, more moderate damage was found in stands with a higher percent of fir, which were in general younger. These stands may become more vulnerable as they age. Stem infestations as indicated by rotholz began appearing between ages 12 and 28. No difference in damage severity was seen between sites or climate zones. This may indicate that given time, lack of competition for fir from other agents (e.g. spruce budworm) and a continuation of current climate conditions, adelgid populations will build up in the region of the study regardless of site and stand characteristics.

Managers concerned about losses from BWA damage should consider a monitoring program. If insects/damages are detected within a stand, then the crown conditions within that stand should be examined periodically. BWA does not bring about immediate mortality as indicated by the rotholz chronologies, so decisions about damage need not be urgent if infestations are light or are detected prior to substantial crown deterioration. Given the similarity of the effects of BWA damage to those of drought, and the amplification of damage with drought, managers should pay close attention to their stands following dry periods. Trees may still be salvageable within several years of mortality, so stands near merchantable size should be visited within 3 years of a drought. Precommercial thinning may be a risky practice in stands with BWA already present or within the immediate area as damage severity tended to be higher in more open stands. Where practical, regeneration of other species should be encouraged.

Unless lethal winter temperatures occur, BWA will continue to infest balsam fir stands and increase its damage as the trees mature in eastern Maine.

References

Amman, G.D. 1970. Phenomena of *Adelges piceae* populations (Homoptera: Phylloxeridae) in North Carolina. Annals of the Entomological Society of America. 63: 1727-1734.

Applequist, M.B. 1958. A simple pith locator for use with off-center increment cores. Journal of Forestry 56: 141.

Atkins, M.D. and A.A. Hall. 1969. Effect of light and temperature on the activity of balsam woolly aphid crawlers. Canadian Entomologist. 101: 481-488.

Atkins, M.D. and T.A.D. Woods. 1968. Survival of the balsam woolly aphid on *Abies* logs. Canadian Entomologist. 100: 412-420.

Bakuzis, E.V. and H.L Hansen. 1965. Balsam fir: A monographic review. The University of Minnesota Press, Minneapolis, MN. 445 pp.

Beck, D.E. 1990. Fraser fir. Pp 47-51 *in* R.S. Burns and B.H. Honkala (eds). Silvics of North America, Vol. 1, Softwoods. USDA Forest Service Agricultural Handbook 654.

Briggs, R. 1994. Site classification field guide. Maine Agricultural and Forest Experiment Station. Miscellaneous Publication 724. CFRU Technical Note 6.

Briggs, R.D and R C. Lemin Jr. 1992. Delineation of climatic regions in Maine. The Canadian Journal of Forest Research. 22: 801-811.

Brower, A.E. 1947. The balsam woolly aphid in Maine. Journal of Economic Entomology 40: 689-694.

Bryant, D.G. 1971. Balsam woolly aphid, *Adelges piceae* (Homoptera: Phylloxeridae), seasonal and spatial development in crowns of balsam fir, *Abies balsamea*. Canadian Entomologist. 103:1411-1420.

Bryant, D.G. 1974. Distribution of first instar nymphs of *Adelges piceae* (Homoptera: Phylloxeridae) on branches of balsam fir, *Abies balsamea*, after colonization. Canadian Entomologist. 106: 1075-1080.

Bryant, D.G. 1976. Distribution, abundance, and survival of the balsam woolly aphid, *Adelges piceae* (Homoptera: Phylloxeridae), on branches of balsam fir, *Abies balsamea*. Canadian Entomologist. 108: 1097-1111.

Carroll, W.J. and D.G. Bryant. 1960. A review of the balsam woolly aphid in Newfoundland. Forestry Chronicle. 36:278-290.

Carter, C. I. 1971. Conifer woolly aphids (Adelgidae) in Britain. Forestry Commission Bulletin No. 42. London, Her Majesty's Stationery Office.51pp.

Chakraborty, T, A N. Raj, and S. Anoopama. 2004. Hypothesis testing. Pp. I-423 to I-471. *In* SYSTAT 11 Statistics. Systat Software, Inc. Richmond, CA.

Clark, R.C., D.O. Greenbank, D.G. Bryant, and J.W.E. Harris. 1971. Biological control of forest pests in Canada 1959-1968: *Adelges piceae* (Ratz.), balsam woolly aphid (Homoptera: Adelgidae). Pp. 113-127 *In* Department of Agriculture Canada. Biological Control Programmes Against Insects and Weeds in Canada. Commonwealth Institute of Biological Control, Technical Communication No. 4. 266 pp.

Cook, E.R. 1987. The decomposition of tree-ring series for environmental studies. Tree-Ring Bulletin. 47: 37-59.

Cook, E., K. Briffa, S.Shiyatov and V. Mazepa. 1990. Tree-ring standardization and growth-trend estimation. Pp. 104-122 *in* Cook, E.R. and L.A. Kairiukstis (eds). Methods of dendrochronology: applications in the environmental sciences. Kluwer Academic Publishers, Dordrecht, The Netherlands. 394 pp.

Dearborn, R.G. and C.A. Granger (eds.). 2001. Forest and shade tree-insect and disease conditions for Maine-A summary of the 2000 situation. MFS, FH&M Div. Summary Report No. 15.

Eckstein, D, J. Hoogesteger and R.L. Holmes. 1991. Insect-related differences in growth of birch and pine at northern treeline in Swedish Lapland. Holarctic Ecology. 14: 18-23.

Felt, E.P. 1910. Recent observations on European insects in America. Journal of Economic Entomology. 3: 340-343.

Field, D.B. 1980. The economic importance of Maine's spruce-fir resource. Maine Agricultural and Forest Experiment Station Miscellaneous Report 227. 34 pp.

Frank, Robert. 1990. Balsam fir. pp.26-35. *in* R.S. Burns and B.H. Honkala (eds). Silvics of North America, Vol. 1, Softwoods. USDA Forest Service Agricultural Handbook 654.

Fritts, H.C. 1971. Dendroclimatology and Dendroecology. Quaternary Research. 1:419-449.

Fritts, H.C. and T.W. Swetnam. 1989. Dendroecology: A tool for evaluating variations in past and present forest environments. Pp. 111-188 *In* Begon, M., A.H. Fitter, E.D. Ford, A. MacFadyen eds. Advances in Ecological Research Vol. 19. Academic press: Harcourt Brace Jovanovich. New York. 357 pp.

Grissino-Mayer, H.D. 2001. Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. Tree-Ring Research. 57:205-221.

Greenbank, D.O. 1970. Climate and the ecology of the balsam woolly aphid. Canadian Entomologist. 102: 546-578.

Hain, F.P. 1988. The balsam woolly adelgid in North America. Pp 87-109. In A.A. Berryman (ed). Dynamics of forest insect populations, patterns, causes, implications. Plenum Press, New York, NY. 603 pp.

Hain, F.P, R.G. Hollingsworth, F.H. Arthur, F. Sanchez, and R.K. Ross. 1991. Adelgid host interactions with special reference to the balsam woolly adelgid in North America. Pp. 271-287 *in* Baranchikov, Y.N., W.J. Mattson, F.P. Hain and T.L. Payne eds. Forest insect guilds: Patterns of interaction with host trees. General technical report NE-153. USDA Forest Service, Northeastern Research Station. Radnor, PA. 400 pp.

Heim JR., R.R. 2002. A review of twentieth-century drought indices used in the United States. Bulletin of the American Meteorological Society. 83:1149-1165.

Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin. 43: 69-78.

Hudak, J. 1976. Microbial deterioration of balsam fir damaged by the balsam woolly aphid in western Newfoundland. PhD Dissertation. College of environmental science. State University of New York. 136 pp.

Irland, L.C., J.B. Dimond, J.L. Stone, J. Falk, E. Baum. 1988. The spruce budworm outbreak in Maine in the 1970's—Assessment and directions for the future. Maine Agricultural Experiment Station. Orono, ME. Bulletin 819. 119 pp.

Jardon, Y., L. Filion, and C. Cloutier. 1994. Tree-ring evidence for the endemicity of larch sawfly in North America. The Canadian Journal of Forest Research. 24: 742-747.

Johnson, N.E., R.G. Mitchell and K.H. Wright. 1963. Mortality and damage to Pacific silver fir by the balsam woolly aphid in southwestern Washington. Journal of Forestry 61: 854-860.

Kotinsky, J. 1916. The European fir trunk bark louse (*Chermes (Dreyfusia) piceae* Ratz.) apparently long established in the United States. Proceedings Entomological Society of Washington. 18: 14-16.

Kloft, W. 1957. Further investigations concerning the interrelationship between bark condition of *Abies alba* and infestation by *Adelges piceae typica* and *A. nüsslini schneideri*. Zeitschrift Für Angewandte Entomologie**.** 41: 438-442

Lombard, Pamela J. 2004. Drought conditions in Maine, 1999-2002: A historical perspective. US Department of Interior. USGS Water-Resources Investigations Report 03-4310. 36 pp.

Mason, R.R., B.E. Wickman, and H. G. Paul. 1997. Radial growth response of Douglas-fir and grand fir to larval densities of the Douglas-fir tussock moth and the western spruce budworm. Forest Science 43:194-205.

McWilliams, W. H., B.J. Butler, L.E. Caldwell, D.M. Griffith, M.L. Hoppus, K. M. Laustsen, A.J. Lister, T.W. Lister, J. Metzler, R.S. Morin, S.A. Sader, , L.B. Stewart, J.R. Steinman, J.A. Westfall, D.A. Williams, A. Whitman , C.W. Woodall. 2005. The forests of Maine,2003. Resour. Bull. NE-164. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 188 pp.

Mitchell, R.G., G.D. Amman, and W.E. Waters. 1970. Balsam woolly aphid. USDA, Forest Service. Forest Insect and Disease Leaflet. 118.

Moesswilde, M.J. 1995. Age structure, disturbance and development of old growth red spruce stands in northern Maine. M.S. Thesis, University of Maine, Orono, Maine. 198 pp.

Morin, H., D. Laprise, and Y. Bergeron. 1992. Chronology of spruce budworm outbreaks near Lake Duparquet, Abitibi region, Quebec. The Canadian Journal of Forest Research. 23: 1497-1506.

Nash, T.H. III, H.C. Fritts, M.A.Stokes. 1975. A technique for examining non-climatic variation in widths of annual tree rings with special reference to air pollution. Tree-Ring Bulletin. 35:15-24.

National Climatic Data Center (NCDC). 2005. Palmer Drought Severity Index: Maine. US Department of Commerce, Asheville, NC. Available for download at: http://www1.ncdc.noaa.gov/pub/data/cirs/

National Climatic Data Center (NCDC). 2005a. Weather station records. US Department of Commerce, Asheville, NC. Available for download at: http://www.ncdc.noaa.gov/oa/climate/stationlocator.html

Nowacki, G.J. M.D. Abrams. 1997. Radial-growth averaging criteria for reconstructing disturbance histories from presettlement-origin oaks. Ecological Monographs, 67: 225-249.

Page, G. 1975. The impact of balsam woolly aphid damage on balsam fir stands in Newfoundland. Canadian Journal of Forest Research. 5: 195-209.

Pilcher, J.R. 1990. Sample preparation, cross-dating and measurement. Pp. 40-51 *In* Cook, E.R. and L.A. Kairiukstis (eds). Methods of dendrochronology: applications in the environmental sciences. Kluwer Academic Publishers, Dordrecht, The Netherlands. 394 pp.

Schooley, H.O. and D.G. Bryant. 1978. The balsam woolly aphid in Newfoundland. Canadian forestry service. Newfoundland forest research center. Information Report. N-X-160. 72 pp.

Schooley, H.O. and L. Oldford. 1974. Damage caused by the balsam woolly aphid in young balsam fir stands. Canadian forestry service, Newfoundland forest research center. Information report N-X-115. 19pp.

Spatial climate analysis service. 2005. Oregon State University. Corvallis, OR. Available for download at: http://mistral.oce.orst.edu/www/mapserv/nn/index.phtml

Speer, J.H., T.W. Swetnam, B.E. Wickman, A. Youngblood. 2001. Changes in pandora moth outbreak dynamics during the past 622 years. Ecology. 82: 679-697.

Smith, G.F. and N.S. Nicholas. 2000. Size-and age-class distributions of Fraser fir following balsam woolly adelgid infestation. The Canadian Journal of Forest Research. 30: 948-957.

Stokes, M.A. and T.L. Smiley. 1996. An introduction to tree-ring dating. University of Arizona Press, Tucson, AZ. 73 pp.

Swetnam, T.W., M.A. Thompsom, and E.K. Sutherland. 1985. Using dendrochronology to measure radial growth of defoliated trees. USDA Forest Service Agricultural Handbook 639. 39 pp.

Swetnam, T.W. and A.M. Lynch. 1993. Multicentury, regional-scale patterns of western spruce budworm outbreaks. Ecological Monographs 63: 399-424.

Triplehorn, C.A., and N.F. Johnson. 2005. Borror and DeLong's introduction to the study of insects. Seventh edition. Thomson Brooks/Cole Belmont, CA. 864 pp.

USDA Forest Service. 2003. Forest Inventory and Analysis national core field guide: version 2.0. (revised 3/2004) USDA Forest Service, Northeastern research station. 124 pp.

Wilkinson, L., L. Engelman, R. Marcantonio. 2004. Correlations, similarities and distance measures. Pp. I-123 to I-156 *In* SYSTAT 11 Statistics. Systat Software, Inc. Richmond, CA.

Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. The Canadian Journal of Forest Research. 21: 414-416.

APPENDIX A
Plot Characteristics

Table A. 1. Plot-level descriptors. Seedling and sapling damage codes defined below.

Plot	Elevation (m)	Slope (%)	Aspect (azimuth)	Site Class	Seedling Damage	Sapling Damage
AUR1	92	8	235	2	3	3
BED1	105	0	0	1	3	3
BUR1	102	15	42	1	3	3
CEN1	97	11	190	2	3	3
CHE1	83	0	0	3	3	3
GRE1	142	0	0	4	3	3
KOS1	168	10	33	1	3	3
KOS2	-	7	5	4	3	3
LIN1	170	5	356	1	3	3
NOR1	59	15	260	2	3	3
OSB1	94	15	75	1	3	3
SPR1	109	0	0	3	3	3
T161	116	12	72	2	3	3
T221	110	3	300	2	3	3
T251	105	8	120	1	3	3
T281	109	6	340	1	3	3
T291	221	0	0	4	3	3
T301	107	0	0	3	4	3
T311	135	0	0	3	3	3
T321	131	0	0	3	3	3
T341	174	17	228	1	3	3
T351	-	0	0	3	3	3
T362	129	0	0	2	3	3
T391	119	0	0	3	1	1
T411	120	0	0	3	3	3
T421	138	5	9	2	4	4
T431	-	6	251	3	3	1
TOP1	151	2	298	1	3	3
TOP2	172	12	53	2	3	3

Seedling/Sapling Damage Codes

1- No balsam fir in that size-class
2- No gout present
3- Gout present
4- Mortality due to gout

Table A. 2. Species composition, basal area, diameter and density. All values are for live tree species at least 12.6 cm in diameter except for fir where values for live, recently dead and snag trees are reported. Nonhost species are indicated in **bold**. Basal area is reported by species in m^2/ha. DBH and standard error are reported in cm and density in number of stems/ha.

	AUR1			BED1			BUR1			CEN1			CHE1		
Species	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**
***Abies balsamea* (live)**	15.7	16.5 ± 0.5	704	3.1	17.0 ± 0.7	136	7.3	18.0 ± 0.9	272	8.1	17.9 ± 1.0	297	4.1	17.2 ± 0.7	173
(recent dead)	1.2	17.4 ± 1.0	49	0.3	17.8 ± 0.0	12	1.0	17.6 ± 3.7	37	0.8	19.5 ± 6.5	25	-	-	-
(snag)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Acer pensylvanicum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Acer rubrum	-	-	-	2.3	15.9 ± 1.3	111	-	-	-	-	-	-	0.5	22.7 ± 0.0	12
Acer saccharum	-	-	-	-	-	-	**5.6**	**19.9 ± 1.0**	**173**	-	-	-	-	-	-
Betula alleghaniensis	-	-	-	-	-	-	1.8	25.0 ± 0.8	37	-	-	-	-	-	-
Betula papyrifera	-	-	-	1.3	21.2 ± 0.6	37	-	-	-	-	-	-	-	-	-
Fagus grandifolia	-	-	-	7.0	19.0 ± 1.0	235	4.4	24.7 ± 2.6	86	-	-	-	-	-	-
Fraxinus americana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ostrya virginiana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea glauca	-	-	-	-	-	-	-	-	-	**1.7**	**20.3 ± 2.7**	**49**	-	-	-
Picea mariana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea rubens	0.2	15.4 ± 0.0	12	**1.3**	**15.9 ± 2.0**	**62**	0.2	15.6 ± 0.0	12	**1.3**	**36.7 ± 0.0**	**12**	**18.1**	**17.3 ± 0.5**	**729**
Pinus strobus	**9.5**	**30 .0± 3.0**	**124**	-	-	-	-	-	-	21.0	30.4 ± 4.7	210	-	-	-
Populus balsamifera	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Populus grandidentata	-	-	-	4.7	38.0 ± 8.8	37	-	-	-	-	-	-	-	-	-
Populus tremuloides	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prunus pensylvanica	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prunus serotina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thuja occidentalis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tsuga canadensis	-	-	-	2.5	18.6 ± 2.0	86	4.6	20.9 ± 2.1	124	-	-	-	-	-	-
Ulmus americana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum BA and Density	25.4		840	22.2		704	23.9		704	32.1		568	22.7		914

Table A. 2 continued

	GRE1			KOS1			KOS2			LIN1			NOR1		
Species	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**
***Abies balsamea* (live)**	10.8	16.7 ± 0.5	482	4.4	19.7 ± 1.6	136	12.9	19.6 ± 0.7	408	9.3	21.2 ± 1.8	235	6.7	16.3 ± 0.6	309
(recent dead)	0.7	15.8 ± 0.2	37	1.3	23.6 ± 10.1	25	0.3	18.4 ± 0.0	12	1.5	21.7 ± 4.2	37	0.5	21.6 ± 0.0	12
(snag)	2.2	16.6 ± 0.8	99	3.0	24.6 ± 1.2	62	0.5	16.3 ± 1.3	25	-	-	-	-	-	-
Acer pensylvanicum	0.4	14.9 ± 0.5	25	-	-	-	-	-	-	-	-	-	-	-	-
Acer rubrum	1.2	25.4 ± 1.2	25	-	-	-	-	-	-	0.6	16.8 ± 3.0	25	0.2	14.3 ± 0.0	12
Acer saccharum	-	-	-	**2.3**	**16.0 ± 1.1**	**111**	-	-	-	-	-	-	-	-	-
Betula alleghaniensis	1.7	18.3 ± 2.2	62	1.9	22.6 ± 8.5	37	-	-	-	-	-	-	-	-	-
Betula papyrifera	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fagus grandifolia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fraxinus americana	-	-	-	2.6	21.6 ± 4.3	62	0.8	28 .0± 0.0	12	-	-	-	-	-	-
Ostrya virginiana	-	-	-	1.5	14.9 ± 0.4	86	0.2	15.1 ± 0.0	12	-	-	-	-	-	-
Picea glauca	0.2	15.0 ± 0.0	12	-	-	-	-	-	-	**2.5**	**35.4 ± 7.1**	**25**	0.2	13.8 ± 0.0	12
Picea mariana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea rubens	**6.9**	**23.0 ± 2.5**	**148**	5.9	23.2 ± 1.4	136	2.7	30.2 ± 2.7	37	-	-	-	1.1	16.4 ± 2.0	49
Pinus strobus	1.1	33.3 ± 0.0	12	-	-	-	-	-	-	-	-	-	**5.1**	**18.4 ± 0.9**	**185**
Populus balsamifera	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Populus grandidentata	-	-	-	-	-	-	-	-	-	1.9	20.2 ± 5.5	49	-	-	-
Populus tremuloides	-	-	-	-	-	-	-	-	-	1.6	17.7 ± 2.5	62	-	-	-
Prunus pensylvanica	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prunus serotina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thuja occidentalis	2.2	34.0 ± 1.4	25	-	-	-	-	-	-	-	-	-	-	-	-
Tsuga canadensis	-	-	-	0.7	26.3 ± 0.0	12	**8.4**	**26.5 ± 1.4**	**148**	-	-	-	1.8	30.9 ± 0.5	25
Ulmus americana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum BA and Density	24.5		791	19.3		580	25		617	15.9		396	15.1		592

Table A. 2 continued

	OSB1			SPR1			T161			T221			T251		
Species	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**
***Abies balsamea* (live)**	4.2	15.8 ± 0.6	210	8.6	17.9 ± 0.8	321	10.7	18.8 ± 0.7	371	9.5	19.8 ± 0.8	297	1.7	15.6 ± 0.9	86
(recent dead)	1.4	18.7 ± 1.1	49	-	-	-	-	-	-	-	-	-	0.4	20.7 ± 0.0	12
(snag)	1.3	14.7 ± 0.5	74	0.3	17.6 ± 0.0	12	-	-	-	-	-	-	0.5	21.9 ± 0.0	12
Acer pensylvanicum	-	-	-	-	-	-	-	-	-	1.4	15.3 ± 0.9	74	-	-	-
Acer rubrum	0.5	15.2 ± 1.8	25	2.0	21.4 ± 4.3	49	-	-	-	-	-	-	2.3	16.8 ± 1.2	99
Acer saccharum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Betula alleghaniensis	-	-	-	-	-	-	-	-	-	3.9	30.7 ± 4.9	49	-	-	-
Betula papyrifera	-	-	-	0.3	16.2 ± 0.0	12	-	-	-	-	-	-	-	-	-
Fagus grandifolia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fraxinus americana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ostrya virginiana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea glauca	-	-	-	0.8	28.2 ± 0.0	12	-	-	-	-	-	-	-	-	-
Picea mariana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea rubens	**4.4**	**18.5 ± 0.9**	**161**	-	-	-	**5.6**	**15.4 ± 0.4**	**297**	**5.4**	**20.8 ± 1.8**	**148**	**11.8**	**24.5 ± 2.1**	**222**
Pinus strobus	-	-	-	-	-	-	-	-	-	-	-	-	3.1	21.2 ± 7.0	62
Populus balsamifera	-	-	-	1.3	18.0 ± 1.1	49	-	-	-	-	-	-	-	-	-
Populus grandidentata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Populus tremuloides	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prunus pensylvanica	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prunus serotina	-	-	-	0.4	19.0 ± 0.0	12	-	-	-	-	-	-	-	-	-
Thuja occidentalis	-	-	-	**10.6**	**30.5 ± 2.5**	**136**	-	-	-	-	-	-	-	-	-
Tsuga canadensis	-	-	-	-	-	-	-	-	-	0.3	16.1 ± 0.0	12	7.1	27.9 ± 2.1	111
Ulmus americana	-	-	-	0.2	14.0 ± 0.0	12	-	-	-	-	-	-	-	-	-
Sum BA and Density	9.1		396	24.2		603	16.3		668	20.5		580	26		580

Table A. 2 continued

	T281			T291			T301			T311			T321		
Species	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**
***Abies balsamea* (live)**	2.3	21.4 ± 2.1	62	2.8	23.9 ± 0.8	62	2.1	17.2 ± 1.4	86	9.1	19.9 ± 1.2	272	3.9	15.7 ± 0.5	198
(recent dead)	2.2	23.5 ± 2.6	49	0.4	21.3 ± 0.0	12	2.1	16.1 ± 1.0	99	2.8	30.6 ± 4.4	37	0.7	15.3 ± 1.0	37
(snag)	1.7	28.1 ± 8.5	25	5.3	21.7 ± 1.6	136	6.5	19.4 ± 1.0	210	-	-	-	-	-	-
Acer pensylvanicum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Acer rubrum	-	-	-	0.3	18.9 ± 0.0	12	14.3	23.0 ± 2.2	284	7.8	20.8 ± 2.2	198	1.8	18.9 ± 2.3	62
Acer saccharum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Betula alleghaniensis	6.4	25.1 ± 3.5	111	0.3	18.8 ± 0.0	12	7.5	28.9 ± 4.2	99	-	-	-	-	-	-
Betula papyrifera	-	-	-	3.0	38.4 ± 8.2	25	-	-	-	1.6	16.2 ± 1.0	74	0.5	13.6 ± 0.4	37
Fagus grandifolia	1.6	15.3 ± 0.9	86	-	-	-	-	-	-	0.6	16.8 ± 1.3	25	-	-	-
Fraxinus americana	1.1	33.9 ± 0.0	12	-	-	-	-	-	-	-	-	-	-	-	-
Ostrya virginiana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea glauca	1.1	23.3 ± 4.3	25	-	-	-	-	-	-	-	-	-	-	-	-
Picea mariana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea rubens	**13.8**	**24.5 ± 2.4**	**247**	**31.6**	**28.4 ± 1.4**	**457**	**7.3**	**19.6 ± 1.5**	**222**	**2.6**	**20.9 ± 2.0**	**74**	**10.2**	**18.8 ± 0.9**	**346**
Pinus strobus	-	-	-	-	-	-	-	-	-	0.6	17.3 ± 3.9	25	2.7	19.3 ± 1.9	86
Populus balsamifera	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Populus grandidentata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Populus tremuloides	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prunus pensylvanica	0.2	15.9 ± 0.0	12	-	-	-	-	-	-	-	-	-	-	-	-
Prunus serotina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thuja occidentalis	-	-	-	-	-	-	-	-	-	-	-	-	9.6	25.5 ± 0.7	185
Tsuga canadensis	4.4	26.4 ± 3.6	74	2.3	23.5 ± 3.5	49	-	-	-	4.7	34.3 ± 3.1	49	5.9	25.0 ± 2.5	111
Ulmus americana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum BA and Density	30.9		629	40.3		617	31.2		691	27		717	34.6		1025

Table A. 2 continued

	T341			T351			T362			T391			T411		
Species	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**
***Abies balsamea* (live)**	10.3	16.6 ± 0.4	469	6.1	23.2 ± 1.8	136	4.8	16.8 ± 0.8	210	4.3	24.9 ± 1.1	86	2.8	14.2 ± 0.5	173
(recent dead)	-	-	-	0.6	24.4 ± 0.0	12	0.9	17.1 ± 1.2	37	1.5	22.3 ± 3.4	37	0.5	16.2 ± 1.2	25
(snag)	-	-	-	-	-	-	-	-	-	-	-	-	3.2	17.8 ± 0.9	124
Acer pensylvanicum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Acer rubrum	-	-	-	1.3	20.0 ± 4.2	37	1.6	40.8 ± 0.0	12	1.7	18.1 ± 2.2	62	0.2	12.8 ± 0.0	12
Acer saccharum	-	-	-	-	-	-	-	-	-	0.5	15.5 ± 0.8	25	-	-	-
Betula alleghaniensis	-	-	-	2.0	15.2 ± 0.6	111	0.4	14.3 ± 1.3	25	1.7	29.2 ± 2.1	25	-	-	-
Betula papyrifera	-	-	-	1.2	17.2 ± 1.7	49	-	-	-	-	-	-	-	-	-
Fagus grandifolia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fraxinus americana	-	-	-	-	-	-	-	-	-	1.7	15.8 ± 0.6	86	-	-	-
Ostrya virginiana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Picea glauca	**3.0**	**17.1 ± 1.1**	**124**	-	-	-	-	-	-	**2.0**	**25.5 ± 4.7**	**37**	-	-	-
Picea mariana	-	-	-	-	-	-	-	-	-	-	-	-	**3.2**	**18.6 ± 1.7**	**111**
Picea rubens	1.1	16.5 ± 1.9	49	**2.5**	**22.2 ± 1.9**	**62**	**24.3**	**23.5 ± 1.2**	**507**	1.1	33.6 ± 0.0	12	-	-	-
Pinus strobus	2.0	18.2 ± 1.5	74	-	-	-	1.7	29.4 ± 2.2	25	-	-	-	-	-	-
Populus balsamifera	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Populus grandidentata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Populus tremuloides	-	-	-	-	-	-	-	-	-	-	-	-	0.6	14.3 ± 0.4	37
Prunus pensylvanica	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prunus serotina	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Thuja occidentalis	-	-	-	6.7	36.6 ± 3.2	62	1.8	21.4 ± 2.4	49	7.2	42.4 ± 4.2	49	-	-	-
Tsuga canadensis	-	-	-	-	-	-	6.7	18.2 ± 1.7	222	5.9	27.3 ± 1.8	99	-	-	-
Ulmus americana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum BA and Density	16.4		716	19.8		457	41.3		1050	26.1		481	6.8		333

Table A. 2 continued

	T421			T431			TOP1			TOP2		
Species	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**	**BA (m^2/ha)**	**DBH (cm) ± se**	**n/ha**
***Abies balsamea* (live)**	5.0	28.9 ± 2.3	74	4.5	17.9 ± 0.8	173	7.2	16.7 ± 0.6	321	10.6	20.8 ± 1.4	284
(recent dead)	4.6	23.8 ± 1.9	99	1.2	20.1 ± 3.2	37	0.6	14.8 ± 1.5	37	-	-	-
(snag)	4.2	24.3 ± 2.2	86	2.0	18.2 ± 1.9	74	0.4	14.1 ± 1.4	25	1.0	22.0 ± 3.1	25
Acer pensylvanicum	-	-	-	-	-	-	-	-	-	-	-	-
Acer rubrum	8.7	22.2 ± 2.7	185	-	-	-	-	-	-	8.5	32.2 ± 2.8	99
Acer saccharum	-	-	-	-	-	-	-	-	-	3.5	19.7 ± 1.5	111
Betula alleghaniensis	3.5	23.6 ± 3.0	74	-	-	-	-	-	-	-	-	-
Betula papyrifera	-	-	-	2.0	18.0 ± 1.9	74	-	-	-	-	-	-
Fagus grandifolia	-	-	-	-	-	-	-	-	-	-	-	-
Fraxinus americana	-	-	-	-	-	-	-	-	-	-	-	-
Ostrya virginiana	-	-	-	-	-	-	-	-	-	0.2	13.4 ± 0.0	12
Picea glauca	**3.3**	**22.8 ± 3.3**	**74**	-	-	-	0.7	25.9 ± 0.0	12	-	-	-
Picea mariana	-	-	-	-	-	-	-	-	-	-	-	-
Picea rubens	1.9	19.3 ± 1.7	62	**19.4**	**20.2 ± 0.8**	**568**	0.5	16.4 ± 1.2	25	**10.0**	**30.1 ± 1.8**	**136**
Pinus strobus	0.2	15.9 ± 0.0	12	-	-	-	**1.7**	**41.4 ± 0.0**	**12**	-	-	-
Populus balsamifera	-	-	-	-	-	-	-	-	-	-	-	-
Populus grandidentata	-	-	-	-	-	-	-	-	-	-	-	-
Populus tremuloides	-	-	-	-	-	-	-	-	-	-	-	-
Prunus pensylvanica	-	-	-	-	-	-	-	-	-	-	-	-
Prunus serotina	-	-	-	-	-	-	-	-	-	-	-	-
Thuja occidentalis	-	-	-	0.3	16.2 ± 0.0	12	-	-	-	-	-	-
Tsuga canadensis	0.3	17.6 ± 0.0	12	11.2	20.3 ± 1.7	297	-	-	-	6.7	24.5 ± 1.7	136
Ulmus americana	-	-	-	-	-	-	-	-	-	-	-	-
Sum BA and Density	22.9		493	37.4		1124	10.1		370	39.5		778

Table A. 3. Balsam woolly adelgid damage frequency by plot. Cells indicate number of occurrences for each damage class.

	BWA Damage Code								
Plot	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
AUR1	-	44	-	9	2	2	-	4	-
BED1	-	4	-	6	-	-	1	1	-
BUR1	-	16	-	6	-	-	-	3	-
CEN1	8	9	-	7	-	-	-	1	1
CHE1	-	9	-	5	-	-	-	-	-
GRE1	3	28	-	6	1	1	-	4	7
KOS1	-	5	-	2	3	1	-	2	5
KOS2	-	12	-	16	3	-	2	1	3
LIN1	-	13	-	3	3	-	-	3	-
NOR1	-	15	1	7	2	-	-	1	-
OSB1	1	4	-	6	1	4	1	9	1
SPR1	-	18	1	7	-	-	-	-	1
T161	4	9	4	8	3	2	-	-	-
T221	1	13	-	10	-	-	-	-	-
T251	-	3	1	3	-	-	-	2	-
T281	-	3	-	2	-	-	-	5	1
T291	-	-	-	3	2	-	-	1	11
T301	-	3	-	2	-	-	1	8	18
T311	-	4	-	13	4	1	-	3	-
T321	3	1	-	10	1	1	-	3	-
T341	-	8	13	17	-	-	-	-	-
T351	-	4	-	7	-	-	-	1	-
T362	-	12	-	4	1	-	-	2	1
T391	-	-	-	4	2	-	1	3	-
T411	-	9	-	5	-	-	-	2	10
T421	-	-	-	5	1	-	-	15	-
T431	-	1	1	12	-	-	-	2	8
TOP1	-	17	1	6	2	-	-	5	-
TOP2	6	7	-	6	1	2	-	-	3

Damage Code	Description
1	No evidence of BWA
2	Gouting no crown dieback
3	Spire top (gout suppression of lateral growth
4	1-25% crown dieback
5	26-50% crown dieback
6	51-75% crown dieback
7	76-99% crown dieback
8	dead, adelgid related
9	other (dead not adelgid related or unknown; missing information

Table A. 4. Plot variables. Latitude is rank transformed; other values are untransformed. **Fir age** is the average age estimated from all fir cores on a plot that had a pith or whose age to pith could be estimated. **Live fir DBH** is the average DBH of all live fir on plot. **Total live BA** is the basal area of all live trees regardless of species. **Live fir BA** is the basal area of all live fir on plot. **Fir (%BA)** is the percent of Total live BA that is in live fir BA. **Total density** is the number of live stems per hectare for all trees at least 12.6 cm dbh, **Fir density** is the number of live fir stems at least 12.6 cm dbh per hectare. Variables that were averaged on a plot have standard errors indicated. Number of trees used in each calculation is indicated in parentheses.

Plot	Site class	Latitude rank	Fir age	Fir height (m), n	Live fir DBH (cm), n	Total live BA(m^2/ha), n	Live fir BA (m^2/ha), n	Fir (% BA)	Total density (stems/ha)	Fir density (stems/ha)
AUR1	2	7	30.4 ± 1.1 (20)	11.3 ± 0.2 (57)	16.5 ± 0.5 (57)	25.42 (68)	15.71 (57)	61.78	840	704
BED1	1	6	55.7 ± 8.7 (3)	11.1 ± 0.7 (11)	17.0 ± 0.7 (11)	22.21 (57)	3.14 (11)	14.12	704	136
BUR1	1	22	54.3 ± 3.4 (8)	12.8 ± 0.8 (22)	18.0 ± 0.9 (22)	23.96 (57)	7.28 (22)	30.38	704	272
CEN1	2	4	40.5 ± 4.0 (17)	12.7 ± 0.4 (24)	17.9 ± 1.0 (24)	32.05 (46)	8.06 (24)	25.14	568	297
CHE1	3	24	49.5 ± 6.0 (11)	13.4 ± 0.5 (14)	17.2 ± 0.7 (14)	22.66 (74)	4.10 (14)	18.09	914	173
GRE1	4	14	63.6 ± 3.6 (20)	14.5 ± 0.4 (39)	16.7 ± 0.5 (39)	24.70 (64)	10.82 (39)	43.82	791	482
KOS1	1	25	53.9 ± 1.7 (9)	14.9 ± 1.2 (11)	19.7 ± 1.6 (11)	19.37 (47)	4.38 (11)	22.64	580	136
KOS2	4	27	54.2 ± 1.3 (23)	14.5 ± 0.5 (33)	19.6 ± 0.7 (33)	24.98 (50)	12.87 (33)	51.54	617	408
LIN1	1	23	40.9 ± 3.9 (11)	13.8 ± 0.7 (19)	21.2 ± 1.8 (19)	15.93 (32)	9.28 (19)	58.24	396	235
NOR1	2	5	31.6 ± 2.0 (17)	11.8 ± 0.3 (25)	16.3 ± 0.6 (25)	15.12 (48)	6.67 (25)	44.11	592	309
OSB1	1	2	38.3 ± 4.4 (13)	9.0 ± 0.4 (17)	15.8 ± 0.6 (17)	9.07 (32)	4.20 (17)	46.28	396	210
SPR1	3	26	49.8 ± 2.6 (14)	13.5 ± 0.5 (26)	17.9 ± 0.8 (26)	23.98 (49)	8.55 (26)	35.67	603	321
T161	2	1	23.9 ± 1.9 (20)	10.1 ± 0.3 (30)	18.8 ± 0.7 (30)	16.35 (54)	10.70 (30)	65.47	668	371
T221	2	3	28.1 ± 0.6 (19)	13.4 ± 0.5 (24)	19.8 ± 0.8 (24)	20.51 (47)	9.49 (24)	46.26	580	297
T251	1	9	41.2 ± 1.8 (5)	13.0 ± 0.2 (7)	15.6 ± 0.9 (7)	26.01 (47)	1.68 (7)	6.46	580	86
T281	1	10	38.5 ± 0.3 (4)	15.5 ± 1.4 (5)	21.4 ± 2.1 (6)	30.98 (51)	2.55 (6)	7.45	629	62
T291	4	8	68.0 ± 3.3 (4)	19.5 ± 0.4 (5)	23.9 ± 0.8 (5)	40.33 (50)	2.79 (5)	6.91	617	62
T301	3	13	54.3 ± 3.4 (7)	13.7 ± 1.0 (7)	17.2 ± 1.4 (7)	31.19 (56)	2.10 (7)	6.74	691	86
T311	3	12	39.2 ± 2.6 (11)	14.4 ± 0.5 (22)	19.9 ± 1.2 (22)	26.96 (58)	9.07 (22)	33.64	717	272
T321	3	11	63.0 ± 4.4 (10)	12.8 ± 0.4 (16)	15.7 ± 0.5 (16)	34.59 (83)	3.87 (16)	11.18	1025	198
T341	1	15	37.2 ± 0.7 (18)	12.3 ± 0.2 (38)	16.6 ± 0.4 (38)	16.39 (58)	10.34 (38)	63.07	716	469
T351	3	16	53.8 ± 4.8 (5)	14.5 ± 1.0 (11)	23.2 ± 1.8 (11)	19.72 (37)	6.05 (11)	30.71	457	136
T362	2	18	67.5 ± 1.5 (16)	16.5 ± 0.4 (17)	16.8 ± 0.8 (17)	41.37 (85)	4.83 (17)	11.68	1050	210

Table A. 4 continued.

Plot	Site class	Latitude rank	Fir age	Fir height (m), n	Live fir DBH (cm), n	Total live BA(m^2/ha), n	Live fir BA (m^2/ha), n	Fir (% BA)	Total density (stems/ha)	Fir density (stems/ha)
T391	3	17	63.3 ± 3.8 (7)	15.7 ± 0.7 (7)	24.9 ± 1.1 (7)	26.02 (39)	4.27 (7)	16.42	481	86
T411	3	19	49.3 ± 0.9 (12)	11.6 ± 0.8 (14)	14.2 ± 0.5 (14)	6.77 (27)	2.77 (14)	41.01	333	173
T421	2	21	57.6 ± 2.0 (10)	20.6 ± 0.7 (6)	28.9 ± 2.3 (6)	23.01 (40)	5.02 (6)	21.81	493	74
T431	3	20	74.1 ± 1.7 (12)	18.5 ± 0.4 (14)	17.9 ± 0.8 (14)	37.32 (91)	4.45 (14)	11.93	1124	173
TOP1	1	28	40.2 ± 1.0 (23)	11.0 ± 0.3 (26)	16.7 ± 0.6 (26)	10.08 (30)	7.24 (26)	71.83	370	321
TOP2	2	29	62.1 ± 0.8 (7)	15.9 ± 0.7 (23)	20.8 ± 1.4 (23)	39.58 (63)	10.64 (23)	26.88	778	284

Table A. 5. Damage variables. Untransformed values of variables. **Damage Index** is the natural log of the mean of BWA damage on plot. **Group 2** is the percent of live and recently dead fir basal area in the more affected fir class. **Trunk phase** is the percent of live fir stems on plot having BWA within the first 1.8 m of the trunk. **Cores with rotholz** is the percent of cores on the plot with evidence of rotholz. Percent **dead** (with the number dead in parentheses) is the percent of fir basal area that is recently dead. **Crown density, Dieback, Transparency** and uncompacted **Live crown ratio** are crown rating values described in the Forest Inventory and Analysis field guide (USDA Forest Service 2003).

Plot	Damage index	Group 2 (% BA)	Trunk phase (% n)	Cores with rotholz (%)	Percent dead (n)	Crown density ± se (n)	Dieback ± se (n)	Transparency ± se (n)	Live crown ratio ± se (n)
AUR1	0.49	38	39	36	7 (4)	34.6 ± 0.8 (57)	4.2 ± 0.8 (57)	13.4 ± 0.5 (57)	68.1 ± 2.5 (57)
BED1	0.81	64	55	43	9 (1)	30.0 ± 3.2 (11)	15.7 ± 8.3 (11)	13.6 ± 1.4 (11)	44.5 ± 6.0 (11)
BUR1	0.61	44	91	65	12 (3)	33.4 ± 1.6 (22)	3.1 ± 1.2 (22)	12.7 ± 0.5 (22)	50.9 ± 3.3 (22)
CEN1	0.39	56	17	23	9 (1)	35.2 ± 1.5 (24)	5.4 ± 1.2 (24)	12.1 ± 0.5 (24)	58.5 ± 3.4 (24)
CHE1	0.31	42	0	38	0 (0)	39.3 ± 0.9 (14)	4.3 ± 1.4 (14)	11.1 ± 0.6 (14)	56.8 ± 4.7 (14)
GRE1	0.54	25	87	40	6 (4)	32.6 ± 1.2 (39)	5.8 ± 1.0 (39)	12.4 ± 0.4 (39)	41.5 ± 1.9 (39)
KOS1	0.96	76	64	59	22 (2)	33.2 ± 2.2 (11)	11.4 ± 4.0 (11)	14.1 ± 1.1 (11)	52.2 ± 6.4 (11)
KOS2	0.71	73	97	61	2 (1)	31.8 ± 1.3 (33)	7.2 ± 1.1 (33)	13.5 ± 0.7 (33)	50.8 ± 2.7 (33)
LIN1	0.74	54	84	53	14 (3)	32.9 ± 1.6 (19)	3.9 ± 1.2 (19)	12.1 ± 0.7 (19)	60.8 ± 3.5 (19)
NOR1	0.48	49	64	37	6 (1)	32.6 ± 1.5 (25)	5.8 ± 1.5 (25)	13.4 ± 0.6 (25)	54.4 ± 2.1 (25)
OSB1	1.30	70	82	67	25 (9)	28.8 ± 2.7 (17)	17.4 ± 5.6 (17)	15.0 ± 1.1 (17)	75.9 ± 4.7 (17)
SPR1	0.24	41	0	0	0 (0)	35.8 ± 1.3 (26)	3.7 ± 0.9 (26)	12.5 ± 0.6 (26)	62.7 ± 2.9 (26)
T161	0.51	46	33	29	0 (0)	36.2 ± 1.6 (30)	9.8 ± 3.4 (30)	11.0 ± 0.4 (30)	80.1 ± 3.2 (30)
T221	0.35	41	58	35	0 (0)	34.6 ± 1.1 (24)	4.0 ± 0.5 (24)	12.7 ± 0.7 (24)	64.8 ± 3.9 (24)
T251	0.89	50	0	6	20 (2)	37.1 ± 1.5 (7)	4.3 ± 1.3 (7)	12.9 ± 1.0 (7)	56.4 ± 2.6 (7)
T281	1.31	41	80	73	49 (5)	36.0 ± 2.9 (5)	4.2 ± 0.8 (5)	13.0 ± 1.2 (5)	47.0 ± 3.4 (5)
T291	1.10	100	60	38	14 (1)	30.0 ± 2.2 (5)	15.0 ± 2.2 (5)	13.0 ± 1.2 (5)	36.0 ± 1.9 (5)
T301	1.46	57	57	43	50 (8)	28.3 ± 4.6 (6)	11.7 ± 9.7 (6)	15.8 ± 2.0 (6)	45.0 ± 8.2 (6)
T311	0.94	91	73	44	24 (3)	33.9 ± 1.1 (22)	11.1 ± 2.3 (22)	14.8 ± 0.9 (22)	46.5 ± 3.9 (22)
T321	0.95	81	44	50	15 (3)	39.4 ± 1.8 (16)	7.5 ± 1.4 (16)	13.4 ± 0.6 (16)	43.4 ± 3.0 (16)
T341	0.37	47	3	11	0 (0)	41.4 ± 0.9 (38)	4.9 ± 0.7 (38)	13.2 ± 0.4 (38)	61.2 ± 2.1 (38)
T351	0.69	82	91	27	9 (1)	34.1 ± 1.8 (11)	8.6 ± 1.4 (11)	13.6 ± 0.7 (11)	70.5 ± 3.9 (11)
T362	0.61	35	47	17	15 (2)	33.2 ± 1.4 (17)	4.7 ± 1.6 (17)	11.8 ± 0.6 (17)	30.3 ± 2.3 (17)
T391	1.31	100	100	80	26 (3)	42.1 ± 1.8 (7)	13.6 ± 6.1 (7)	15.7 ± 1.3 (7)	44.3 ± 4.7 (7)

Table A. 5 continued.

Plot	Damage index	Group 2 (% BA)	Trunk phase (% n)	Cores with rotholz (%)	Percent dead (n)	Crown density ± se (n)	Dieback ± se (n)	Transparency ± se (n)	Live crown ratio ± se (n)
T411	0.66	51	29	21	16 (2)	31.4 ± 1.8 (14)	4.3 ± 0.7 (14)	10.4 ± 0.4 (14)	47.1 ± 4.7 (14)
T421	1.59	70	33	50	48 (15)	32.5 ± 4.2 (6)	13.3 ± 3.3 (6)	11.7 ± 1.1 (6)	28.3 ± 2.8 (6)
T431	0.86	89	57	6	22 (2)	37.1 ± 1.1 (14)	6.1 ± 0.6 (14)	12.1 ± 0.7 (14)	32.5 ± 2.1 (14)
TOP1	0.76	43	100	65	8 (5)	36.0 ± 1.3 (26)	5.2 ± 1.2 (26)	14.6 ± 0.7 (26)	69.0 ± 2.6 (26)
TOP2	0.49	62	70	60	0 (0)	32.8 ± 1.8 (23)	5.5 ± 1.6 (23)	15.2 ± 0.7 (23)	46.1 ± 3.4 (23)

APPENDIX B
Growth Change Mean Comparisons and Sign Tests Results

Table B. 1. P-values for mean comparisons between less affected and more affected fir groups. Significant P-values indicate that growth trends of more affected fir were lower than less affected fir. P<0.1 indicated in bold.

Year	AUR1	CEN1	CHE1	GRE1	KOS2	LIN1	NOR1	OSB1	SPR1	T161	T221	T341	T362	T411	TOP1
1957	.	.	.	0.294	0.935	.	.	.	.	.	.	.	0.814	.	.
1958	.	.	.	0.110	0.729	.	.	.	.	.	.	.	**0.082**	.	.
1959	.	.	.	0.135	0.209	.	.	.	.	.	.	.	0.803	.	.
1960	.	.	.	0.122	0.426	.	.	.	.	.	.	.	0.641	.	.
1961	.	.	.	**0.075**	0.325	.	.	.	.	.	.	.	0.810	.	.
1962	.	.	.	0.395	0.181	.	.	.	.	.	.	.	0.590	.	.
1963	.	.	.	0.790	0.180	.	.	.	.	.	.	.	0.647	.	.
1964	.	.	.	0.675	0.847	.	.	.	.	.	.	.	**0.100**	0.973	.
1965	.	.	.	0.658	0.852	.	.	.	0.680	.	.	.	**0.010**	0.975	.
1966	.	.	.	0.586	0.837	.	.	.	0.699	.	.	.	**0.003**	0.924	.
1967	.	.	.	0.974	0.911	.	.	.	.	.	.	.	0.220	0.486	.
1968	.	.	.	0.961	0.981	.	.	.	0.445	.	.	.	0.772	0.402	.
1969	.	.	.	0.730	0.975	.	.	.	0.265	.	.	.	0.844	0.140	.
1970	.	.	.	0.516	0.949	.	.	.	0.126	.	.	.	0.645	0.235	0.163
1971	.	.	.	0.587	0.894	.	.	.	0.292	.	.	.	0.818	**0.085**	0.308
1972	.	.	.	0.892	0.458	.	.	.	0.352	.	.	.	0.887	0.356	0.638
1973	.	.	.	0.822	0.622	.	.	.	0.127	.	.	0.919	0.894	0.205	0.722
1974	.	.	0.758	0.837	0.562	.	.	.	0.112	.	.	0.364	0.510	0.408	0.145
1975	.	.	0.783	0.697	0.676	.	.	.	0.328	.	.	0.721	0.288	0.157	**0.025**
1976	.	**0.065**	0.828	0.655	0.453	.	.	.	0.314	.	.	0.962	0.389	0.130	**0.008**
1977	.	0.162	0.892	**0.098**	0.236	.	.	.	0.439	.	.	0.979	0.673	0.343	**0.033**
1978	.	0.413	0.997	**0.091**	0.210	.	.	.	0.207	.	.	0.877	0.849	0.819	0.368
1979	0.260	0.868	0.998	**0.086**	0.269	.	.	.	**0.061**	.	.	0.346	0.869	0.900	0.214
1980	0.655	0.636	0.996	0.587	**0.082**	.	.	.	**0.004**	.	**0.043**	**0.060**	0.891	0.581	**0.026**
1981	0.653	0.661	0.955	0.558	0.511	**0.000**	.	.	**0.036**	.	**0.022**	**0.053**	0.663	0.256	0.436
1982	0.239	0.812	0.249	0.816	0.228	0.983	.	.	0.104	.	**0.006**	0.185	0.254	0.203	0.545
1983	0.265	0.220	0.165	0.744	0.412	0.694	0.214	.	**0.074**	.	**0.077**	0.517	**0.065**	0.429	0.732
1984	0.743	**0.099**	0.279	0.771	0.482	0.132	0.195	.	**0.055**	.	0.550	0.682	**0.025**	0.500	0.813
1985	0.960	**0.001**	0.688	0.466	0.666	0.146	0.350	.	0.477	.	0.943	0.462	**0.007**	0.616	0.711
1986	0.992	**0.002**	0.496	**0.070**	0.600	0.123	0.375	.	0.680	.	0.945	0.238	**0.045**	0.791	0.977
1987	.	**0.006**	**0.060**	0.104	0.728	0.128	**0.017**	.	0.893	.	0.815	0.117	0.142	0.514	0.917
1988	0.153	0.328	**0.016**	0.212	0.655	0.503	.	.	0.644	.	0.679	**0.078**	.	0.118	0.296
1989	**0.002**	0.795	**0.002**	0.445	0.548	0.908	.	.	0.696	0.485	0.818	**0.091**	0.232	.	**0.041**
1990	**0.001**	0.969	**0.001**	0.557	0.396	0.750	0.752	.	0.687	0.342	0.889	0.414	0.476	**0.027**	**0.011**
1991	0.175	0.941	**0.000**	0.464	0.355	0.611	.	.	0.668	0.416	0.755	0.220	0.610	0.159	0.119
1992	**0.009**	0.925	**0.079**	**0.044**	0.432	0.400	0.304	.	0.315	0.603	0.193	0.579	0.616	0.158	0.163
1993	0.464	0.976	0.210	**0.027**	0.314	0.281	0.925	.	**0.030**	0.395	**0.100**	0.185	0.318	**0.018**	0.120
1994	0.168	0.882	0.302	**0.067**	0.143	0.112	0.618	.	**0.014**	**0.077**	0.298	0.131	0.277	0.432	**0.087**
1995	0.566	0.871	0.401	**0.062**	**0.039**	0.390	0.889	.	**0.004**	**0.040**	0.819	0.135	0.351	0.534	0.829
1996	0.858	0.237	0.397	0.109	**0.046**	0.375	0.884	.	0.157	**0.046**	0.849	0.133	0.609	0.406	0.670
1997	0.992	0.119	0.127	**0.095**	**0.055**	0.202	0.250	0.359	0.266	0.183	0.609	.	0.609	0.202	0.892
1998	0.422	**0.000**	**0.011**	**0.098**	0.130	**0.008**	**0.056**	0.592	0.236	0.199	0.314	0.317	0.426	0.264	0.231
1999	0.125	**0.001**	**0.040**	0.216	0.400	0.240	**0.088**	0.643	0.242	0.207	.	0.163	0.506	0.308	0.117
2000	**0.006**	0.174	0.347	0.246	0.167	**0.046**	**0.027**	0.363	**0.062**	0.267	0.388	**0.055**	0.551	0.378	**0.026**
2001	**0.008**	**0.001**	0.888	0.118	0.200	**0.099**	**0.010**	**0.057**	**0.029**	**0.081**	**0.068**	0.147	0.542	0.116	**0.092**

Table B. 2. Sign test results for comparisons between less affected (group1) and more affected (group2) fir. Data shown for years in which at least half of the plots were compared. Significant P-values in bold (P<0.1) indicate lower growth trend of more affected fir was a region-wide event.

Year	Frequency no difference	Frequency Group 2<Group 1 (sign value)	Total plots	P-value
1973	0	1	7	0
1974	0	1	8	0
1975	0	1	7	1
1976	0	1	7	2
1977	0	1	7	2
1978	0	1	8	1
1979	8	2	10	0.945
1980	6	5	11	0.500
1981	8	4	12	0.806
1982	11	1	12	0.997
1983	10	3	13	0.954
1984	10	3	13	0.954
1985	11	2	13	0.989
1986	10	3	13	0.954
1987	9	3	12	0.927
1988	9	2	11	0.967
1989	8	4	12	0.806
1990	10	4	14	0.910
1991	12	1	13	0.998
1992	11	3	14	0.971
1993	10	4	14	0.910
1994	10	4	14	0.910
1995	10	4	14	0.910
1996	12	2	14	0.994
1997	12	2	14	0.994
1998	10	5	15	0.849
1999	11	3	14	0.971
2000	9	6	15	0.696
2001	6	9	15	0.151

Table B. 3. P-values for mean comparisons between more affected fir and nonhost tree groups. Significant P-values indicate that growth trends of more affected fir were lower than nonhost. P<0.1 indicated in bold.

Plot	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
AUR1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.195	0.517
BED1	**0.078**	**0.026**	**0.022**	0.227	0.938	.	0.911	0.952	0.955	0.586	0.971	.	0.917	0.938	0.844	0.999	0.998	0.934	**0.008**	**0.016**	**0.033**	0.824	0.962
BUR1	0.171	**0.004**	**0.009**	**0.015**	0.530	0.692	0.927	0.414	0.288	**0.083**	**0.085**	0.125	**0.064**	0.195	0.278	.	.	0.273	0.625	0.681	0.772	0.193	**0.087**
CEN1	.	.	.	.	.	.	.	0.228	0.895	0.788	.	**0.007**	**0.011**	**0.006**	0.139	0.506	0.581	0.200	0.110	**0.025**	0.151	0.992	0.966
CHE1	.	.	**0.035**	0.251	0.891	0.987	0.991	0.876	0.429	0.239	0.215	0.400	0.681	0.824	0.615	0.539	0.989	0.989	0.557	0.563	0.616	0.817	0.966
GRE1	0.217	0.225	0.166	0.351	0.992	**0.000**	**0.000**	0.976	0.774	0.288	0.117	**0.077**	0.211	0.441	0.843	0.917	0.913	**0.017**	**0.004**	**0.002**	**0.016**	**0.040**	0.256
KOS1	**0.041**	**0.039**	0.130	0.150	0.919	0.816	0.818	0.906	0.984	0.835	0.576	0.149	0.208	0.306	**0.067**	0.467	0.244	0.310	0.331	0.250	**0.096**	.	**0.014**
KOS2	0.851	0.922	0.620	0.735	0.369	0.671	0.694	0.986	0.859	0.756	0.201	0.267	0.287	0.399	0.352	**0.096**	0.201	0.479	0.973	0.639	**0.047**	**0.003**	0.432
LIN1	**0.035**	**0.026**	0.284	0.778	0.964	0.674	0.344	0.110	0.914	0.614	0.635	0.633	0.967	0.890	0.959	0.978	0.959	0.937	0.614	**0.080**	0.368	0.655	**0.000**
NOR1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
OSB1	.	.	0.773	0.473	**0.068**	0.393	0.408	0.298	0.117	**0.039**	**0.014**	**0.013**	**0.022**	0.159	0.707	0.770	0.659	0.241	0.288	**0.097**	0.727	0.984	**0.000**
SPR1	**0.004**	0.639	0.832	0.821	.	0.928	0.848	0.851	0.856	0.878	0.627	0.467	0.409	0.239	0.396	0.817	0.926	0.314	0.158	**0.000**	**0.000**	**0.000**	**0.006**
T161	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
T221	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
T251	.	.	.	.	.	.	.	.	.	0.954	0.724	0.804	**0.027**	**0.037**	.	**0.021**	0.495	0.383	0.174	0.153	0.541	0.990	0.975
T281	.	.	.	.	.	.	.	.	.	.	.	.	.	0.906	0.935	0.985	0.702	0.371	0.289	0.554	0.262	0.416	0.706
T291	0.597	0.888	0.971	0.999	1.000	0.916	**0.099**	**0.010**	0.278	0.599	0.971	0.703	0.442	**0.072**	0.555	0.573	0.710	**0.098**	**0.002**	**0.001**	0.173	0.966	**0.000**
T301	0.223	**0.054**	**0.025**	0.149	0.456	0.772	0.727	0.920	0.914	0.976	0.993	0.584	**0.044**	**0.011**	**0.030**	0.150	0.793	0.695	0.809	0.973	0.982	0.999	0.993
T311	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	**0.070**	**0.047**	**0.001**	**0.008**	**0.008**
T321	**0.001**	**0.010**	0.245	0.385	0.330	0.155	.	0.878	0.641	0.386	0.589	0.155	0.120	**0.081**	0.700	0.914	0.589	**0.071**	0.402	0.481	0.895	0.790	0.532
T341	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.615	0.188	0.212	**0.090**	0.942	0.990	0.752
T351	.	.	**0.050**	0.811	0.764	0.756	0.479	0.529	0.762	0.372	**0.072**	**0.010**	**0.003**	**0.068**	0.248	0.938	0.991	0.975	0.844	0.220	0.208	0.284	0.429
T362	**0.025**	.	0.318	0.344	0.861	0.988	1.000	0.987	0.534	**0.069**	**0.099**	0.512	0.694	0.796	0.928	0.934	0.759	0.365	**0.053**	**0.043**	**0.034**	**0.058**	**0.036**
T391	0.712	0.754	.	0.537	0.926	0.750	0.550	0.520	0.619	0.747	0.672	.	0.830	0.741	0.731	0.220	**0.057**	**0.078**	0.368	0.429	0.259	0.284	0.500
T411	0.868	0.770	0.647	0.700	0.206	0.405	0.156	0.722	0.725	0.900	0.137	**0.053**	**0.004**	0.302	0.937	0.786	1.000	0.999	0.989	0.635	0.581	0.758	0.999
T421	.	.	.	.	.	.	0.621	0.771	0.990	0.998	0.996	**0.000**	0.999	0.784	0.311	0.390	0.466	0.557	0.426	**0.023**	**0.006**	**0.008**	0.601
T431	0.670	0.425	0.985	0.996	0.995	0.743	0.997	0.996	0.996	0.564	**0.047**	**0.017**	**0.016**	0.278	0.799	0.532	0.429	**0.070**	0.165	**0.003**	**0.009**	**0.000**	**0.002**
TOP1	.	.	.	.	.	0.906	0.149	**0.018**	**0.013**	**0.001**	**0.003**	0.228	0.144	0.407	0.497	0.898	0.996	0.999	**0.099**	**0.006**	**0.004**	0.308	.

TOP2	**0.072**	0.251	0.655	0.567	0.527	0.781	0.983	0.985	0.979	0.874	0.785	0.149	0.726	0.612	0.755	0.473	0.773	0.208	0.516	0.321	0.773	0.486	.

Table B. 3 continued.

Plot	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
AUR1	0.277	**0.027**	**0.007**	**0.020**	**0.035**	**0.091**	**0.065**	0.236	.	**0.037**	**0.000**	0.198	**0.073**	0.535	0.943	0.999	0.848	0.819	**0.003**	**0.014**	**0.000**	**0.001**
BED1	0.997	0.993	0.864	0.987	0.769	**0.056**	**0.002**	**0.009**	0.109	0.386	0.441	0.162	0.183	0.819	0.976	0.990	0.789	**0.022**	**0.000**	**0.001**	0.495	**0.041**
BUR1	**0.005**	**0.009**	**0.002**	**0.077**	0.808	0.999	0.997	0.773	0.558	**0.062**	**0.015**	0.430	0.708	0.542	**0.000**	**0.000**	0.884	0.865	0.322	0.152	**0.004**	**0.001**
CEN1	0.998	0.631	0.703	0.385	**0.054**	**0.001**	**0.002**	**0.032**	0.827	0.854	0.907	0.617	0.738	0.985	0.993	0.998	0.957	0.534	0.131	0.312	0.486	**0.023**
CHE1	0.985	0.964	0.917	0.987	**0.000**	0.928	0.948	0.791	0.570	0.301	**0.095**	**0.005**	**0.027**	**0.050**	0.696	0.992	0.722	**0.003**	**0.000**	**0.000**	**0.000**	**0.022**
GRE1	0.105	**0.003**	**0.000**	**0.000**	0.144	0.930	0.977	0.981	0.998	0.950	0.364	0.277	0.146	0.893	0.980	0.984	0.697	**0.011**	**0.001**	**0.001**	**0.045**	**0.010**
KOS1	**0.055**	0.620	0.738	0.890	0.987	0.997	0.991	0.674	0.465	0.222	0.450	0.224	.	0.594	0.576	**0.000**	**0.000**	**0.000**	0.266	**0.009**	**0.004**	**0.023**
KOS2	0.347	0.305	0.744	0.801	0.855	0.858	0.672	0.653	0.532	0.480	0.736	0.201	0.233	0.161	0.291	**0.018**	**0.002**	**0.007**	0.185	0.933	0.853	0.909
LIN1	**0.000**	**0.000**	**0.000**	0.568	**0.064**	**0.004**	**0.006**	**0.008**	**0.009**	0.120	**0.014**	**0.007**	**0.026**	0.911	0.999	0.999	0.994	0.230	**0.022**	**0.022**	**0.081**	.
NOR1	.	.	.	**0.005**	**0.001**	**0.009**	**0.085**	0.933	0.994	0.740	0.779	0.588	0.500	0.946	**0.009**	0.290	**0.090**	0.187	**0.001**	**0.096**	**0.026**	0.210
OSB1	0.998	0.694	0.454	.	0.279	0.352	0.961	0.983	0.708	0.109	**0.057**	**0.080**	**0.057**	0.245	0.340	0.587	0.106	**0.028**	**0.010**	0.230	**0.080**	**0.037**
SPR1	0.286	**0.053**	**0.006**	**0.023**	0.957	**0.000**	0.998	0.998	0.797	**0.000**	0.997	0.904	0.886	0.643	0.701	**0.062**	**0.040**	0.329	**0.004**	**0.002**	**0.000**	**0.000**
T161	.	.	.	.	.	0.306	**0.098**	**0.034**	**0.011**	**0.066**	**0.093**	0.434	0.317	0.138	**0.004**	**0.010**	**0.000**	**0.003**	**0.006**	0.642	0.500	**0.090**
T221	0.849	0.469	0.207	0.165	0.400	0.161	0.645	0.769	0.888	0.465	0.101	0.168	0.125	0.684	.	0.675	0.391	.	**0.095**	**0.067**	0.429	0.436
T251	0.821	0.506	0.251	0.529	0.736	0.774	0.506	0.128	**0.025**	0.352	**0.017**	**0.015**	0.116	.	0.530	0.977	0.804	0.385	**0.000**	**0.001**	**0.004**	0.120
T281	0.696	0.520	0.340	0.678	0.933	0.940	0.933	0.805	0.560	0.349	**0.023**	0.135	0.176	0.946	0.992	0.922	0.296	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**
T291	0.999	0.975	0.452	0.302	0.253	0.452	0.522	0.583	0.350	**0.075**	**0.006**	**0.051**	0.272	0.928	0.784	0.882	0.966	0.328	**0.059**	**0.004**	**0.011**	**0.017**
T301	.	0.999	0.999	0.964	0.667	**0.067**	**0.014**	**0.012**	**0.025**	**0.019**	**0.004**	**0.002**	**0.030**	0.364	0.905	0.815	.	0.433	**0.092**	**0.048**	**0.001**	**0.000**
T311	**0.022**	**0.008**	**0.017**	**0.031**	**0.067**	**0.021**	**0.084**	**0.019**	**0.017**	**0.002**	**0.001**	**0.002**	**0.060**	0.935	0.838	**0.000**	0.989	0.314	**0.051**	0.122	0.325	**0.088**
T321	0.964	0.774	0.895	0.984	0.588	0.929	0.616	0.991	0.536	**0.095**	**0.043**	0.454	**0.006**	0.473	0.961	0.997	0.978	0.234	**0.000**	**0.001**	**0.006**	0.251
T341	**0.001**	**0.000**	**0.000**	**0.001**	**0.002**	0.105	0.722	0.971	0.925	0.781	.	**0.072**	0.379	0.997	0.997	**0.000**	0.991	0.395	0.387	.	0.420	**0.000**
T351	0.314	**0.005**	**0.011**	0.240	0.818	0.998	0.986	0.577	0.212	**0.024**	**0.014**	0.229	0.495	0.639	0.544	0.951	0.815	0.197	**0.015**	0.114	0.106	0.258
T362	**0.003**	**0.000**	**0.068**	0.816	0.997	1.000	0.999	0.768	**0.026**	0.123	0.185	0.534	0.639	0.948	0.994	**0.000**	0.999	0.940	**0.019**	**0.001**	**0.001**	**0.004**
T391	0.447	**0.015**	**0.005**	**0.095**	0.768	0.946	0.973	0.758	0.707	0.480	.	**0.017**	0.316	0.985	1.000	1.000	0.999	0.536	**0.000**	**0.001**	**0.018**	**0.022**
T411	**0.000**	0.997	0.935	0.343	0.144	**0.002**	**0.002**	**0.007**	**0.007**	**0.015**	**0.008**	**0.019**	**0.011**	0.482	0.683	0.764	**0.009**	**0.000**	**0.000**	**0.000**	0.146	0.965
T421	0.847	0.945	0.997	**0.000**	0.992	0.595	0.440	0.629	0.582	0.103	**0.003**	**0.007**	0.649	**0.000**	**0.000**	**0.000**	0.995	**0.033**	**0.000**	**0.000**	**0.000**	**0.001**
T431	**0.020**	0.159	0.836	0.708	0.999	0.998	0.899	**0.042**	**0.008**	**0.001**	**0.000**	**0.001**	**0.006**	0.750	0.964	0.999	0.599	**0.016**	0.197	**0.000**	**0.000**	**0.000**
TOP1	**0.048**	**0.017**	**0.086**	0.951	0.999	1.000	0.943	0.958	0.404	0.408	**0.095**	0.185	**0.047**	**0.069**	**0.081**	0.185	0.343	0.810	0.926	0.880	**0.096**	**0.040**

TOP2	**0.042**	**0.063**	**0.037**	0.343	0.799	0.917	.	.	0.279	**0.053**	**0.001**	**0.003**	0.104	0.773	0.990	**0.000**	1.000	0.324	**0.000**	**0.000**	**0.000**	**0.000**

Table B. 4. Sign test results for comparisons between more affected fir (group2) and nonhost (group3). Data shown for years in which at least half the plots were compared. Significant P-values in bold (P<0.1) indicate lower growth trend of more affected fir was a region-wide event.

Year	Frequency no difference	Frequency Group 2<Group 3 (sign value)	Total plots	P-value
1959	12	5	17	0.928
1960	17	1	18	1.000
1961	16	1	17	1.000
1962	17	1	18	1.000
1963	17	2	19	1.000
1964	19	2	21	1.000
1965	20	1	21	1.000
1966	18	4	22	0.998
1967	15	6	21	0.961
1968	13	7	20	0.868
1969	14	8	22	0.857
1970	17	6	23	0.983
1971	20	2	22	1.000
1972	20	2	22	1.000
1973	22	1	23	1.000
1974	19	5	24	0.997
1975	19	6	25	0.993
1976	12	13	25	0.345
1977	15	10	25	0.788
1978	18	7	25	0.978
1979	15	9	24	0.846
1980	16	10	26	0.915
1981	15	12	27	0.779
1982	15	12	27	0.779
1983	18	9	27	0.973
1984	21	7	28	0.998
1985	20	9	29	0.987
1986	19	9	28	0.981
1987	20	8	28	0.993
1988	20	8	28	0.993
1989	17	12	29	0.867
1990	9	18	27	**0.062**
1991	16	13	29	0.771
1992	18	10	28	0.956
1993	25	3	28	1.000
1994	23	5	28	1.000
1995	19	10	29	0.968
1996	22	6	28	0.999
1997	17	11	28	0.907
1998	7	22	29	**0.005**
1999	8	20	28	**0.019**
2000	9	20	29	**0.032**
2001	7	21	28	**0.007**

APPENDIX C
ARSTAN Standard Chronologies and Precipitation Indices

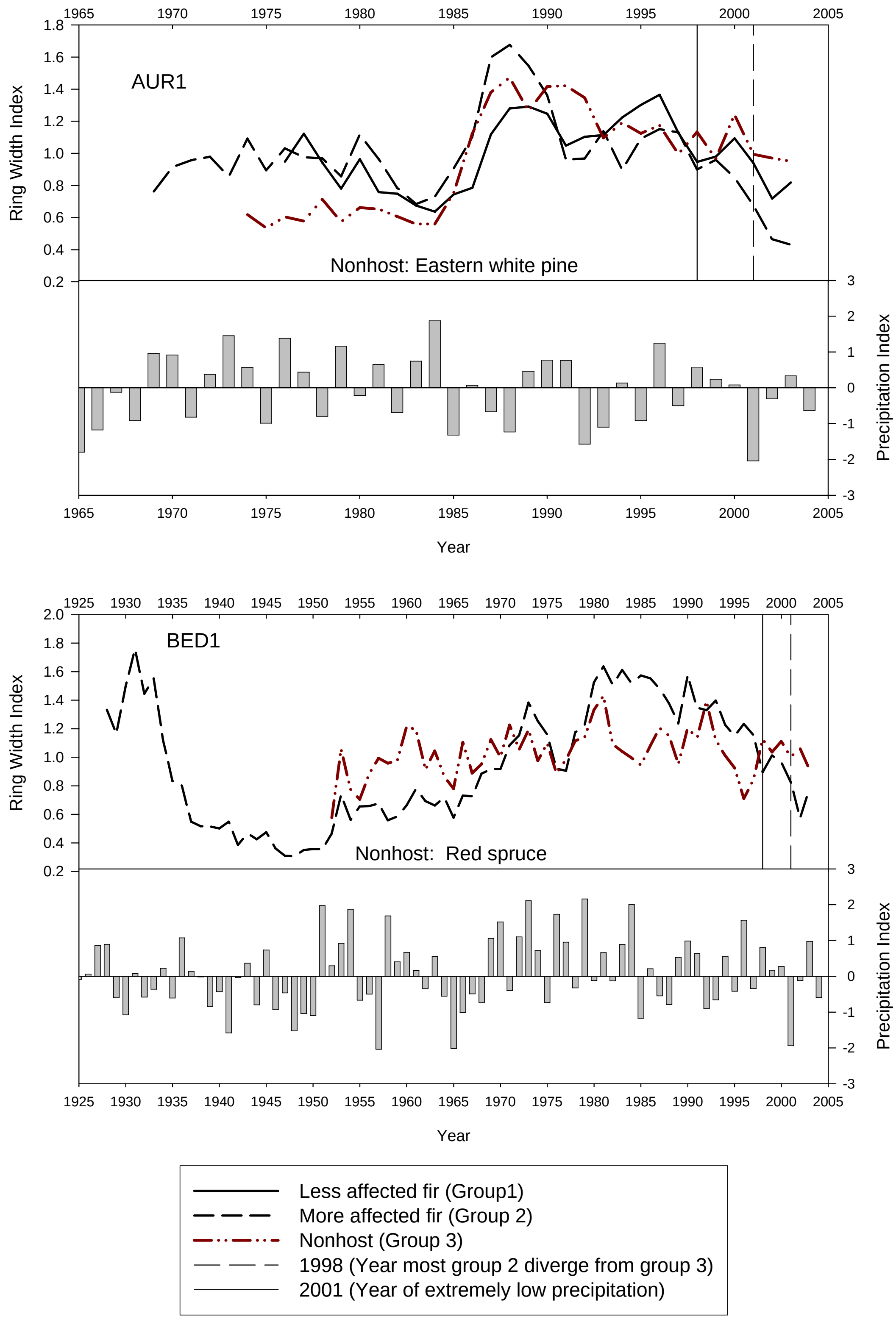


Figure C. 1. Average chronologies for less affected fir, more affected fir and nonhost with precipitation index. Vertical lines indicate year most plots growth trends diverged (1998) and first year of two year period of severe drought (2001).

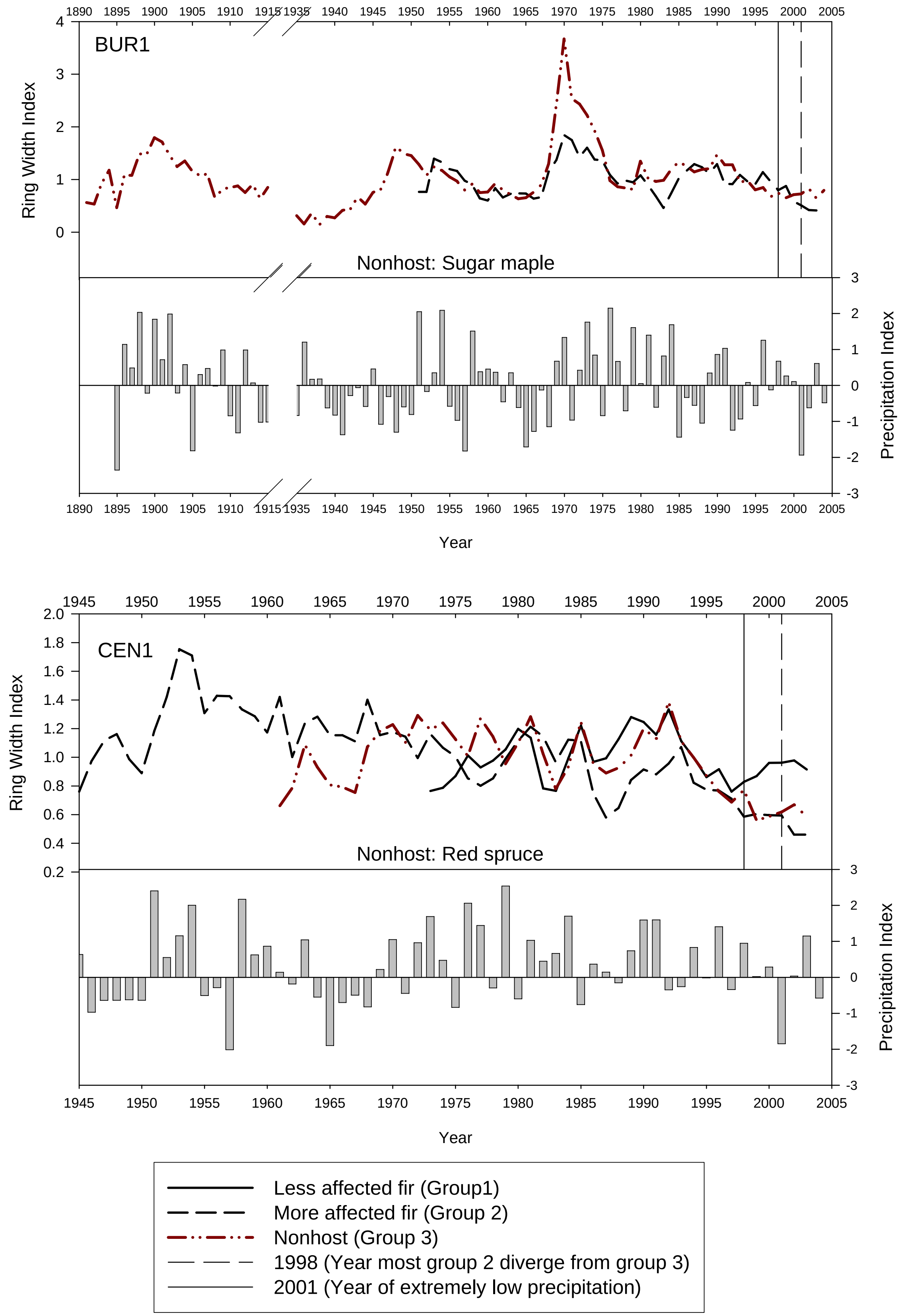


Figure C. 1 continued.

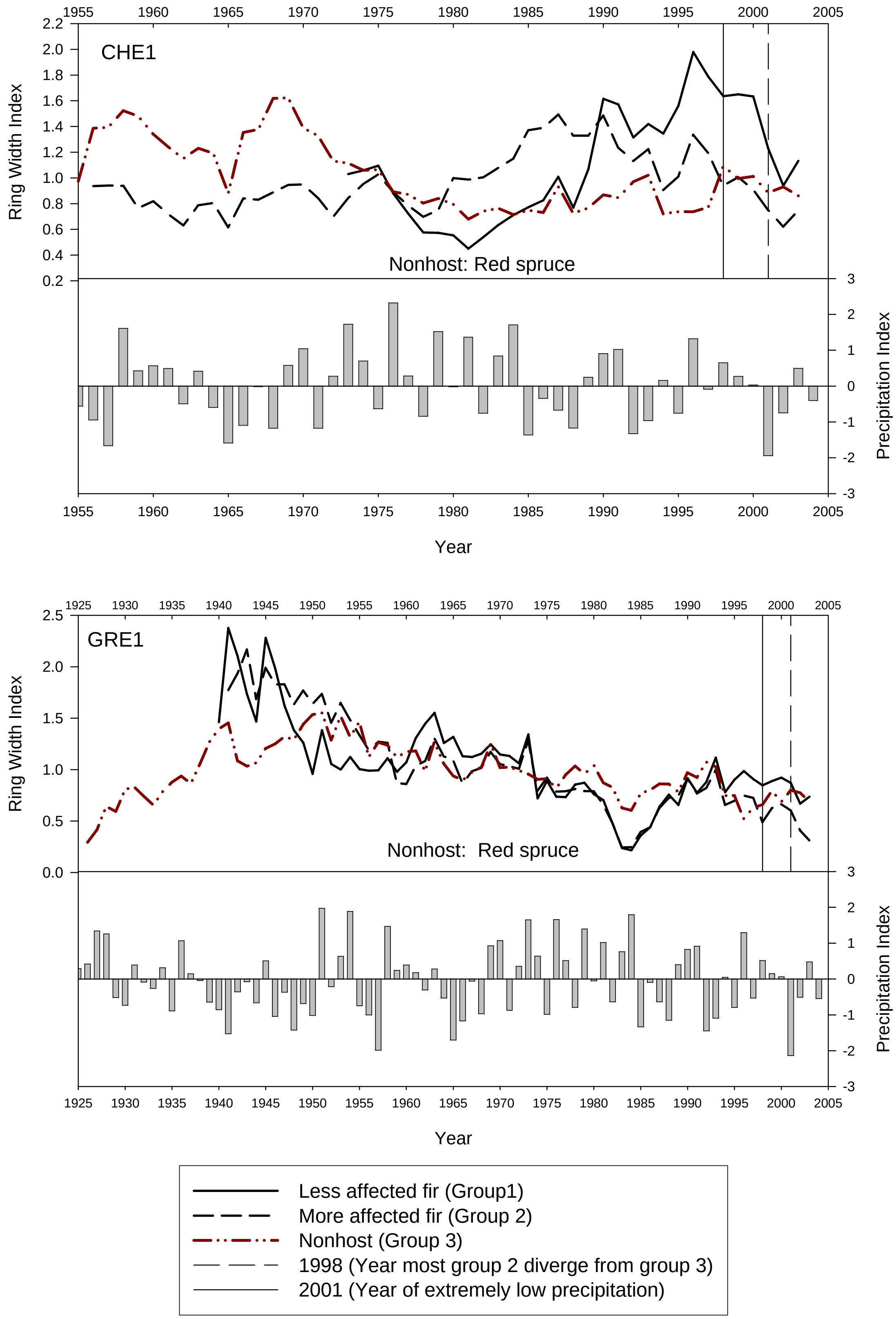


Figure C. 1 continued.

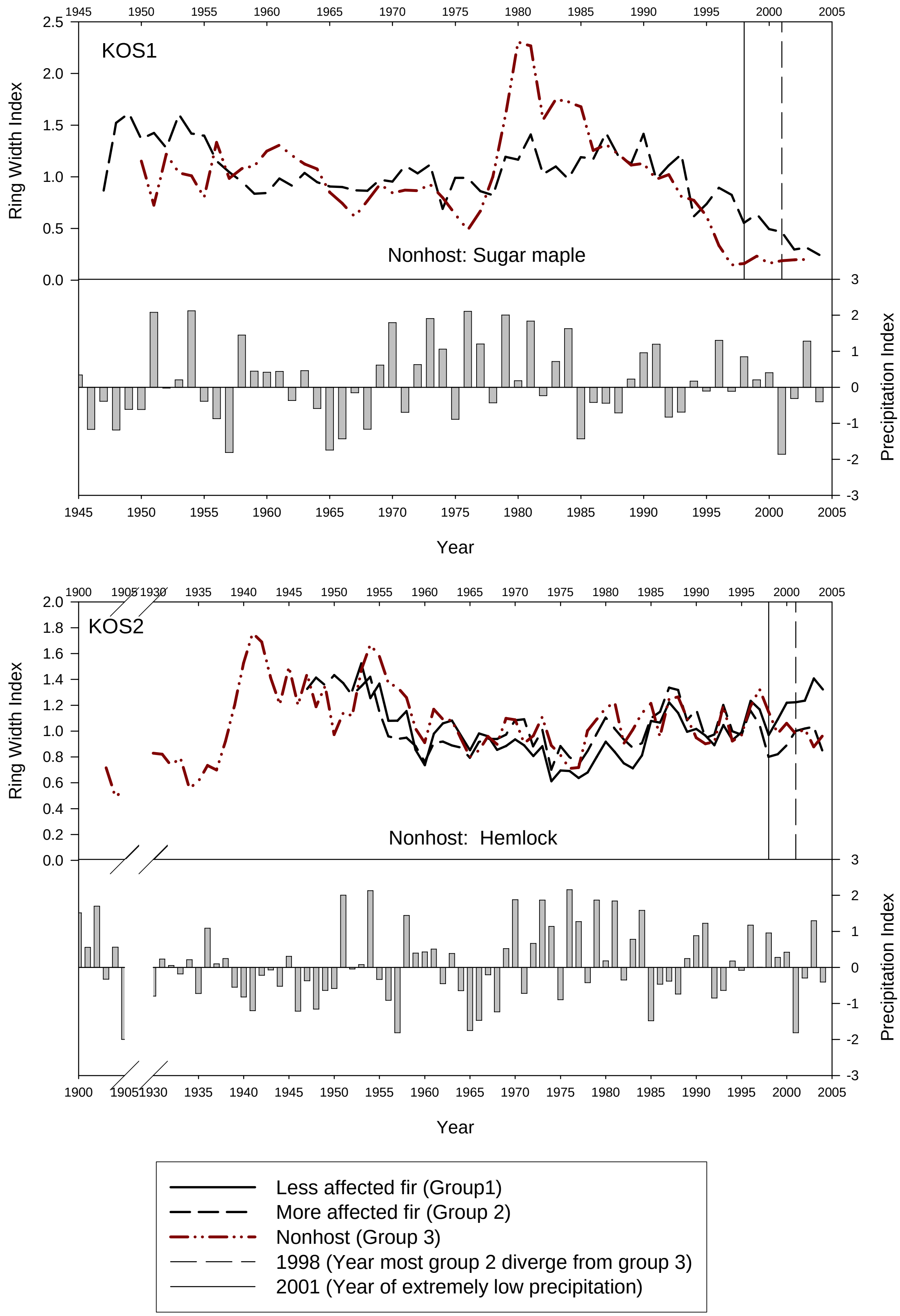


Figure C. 1 continued.

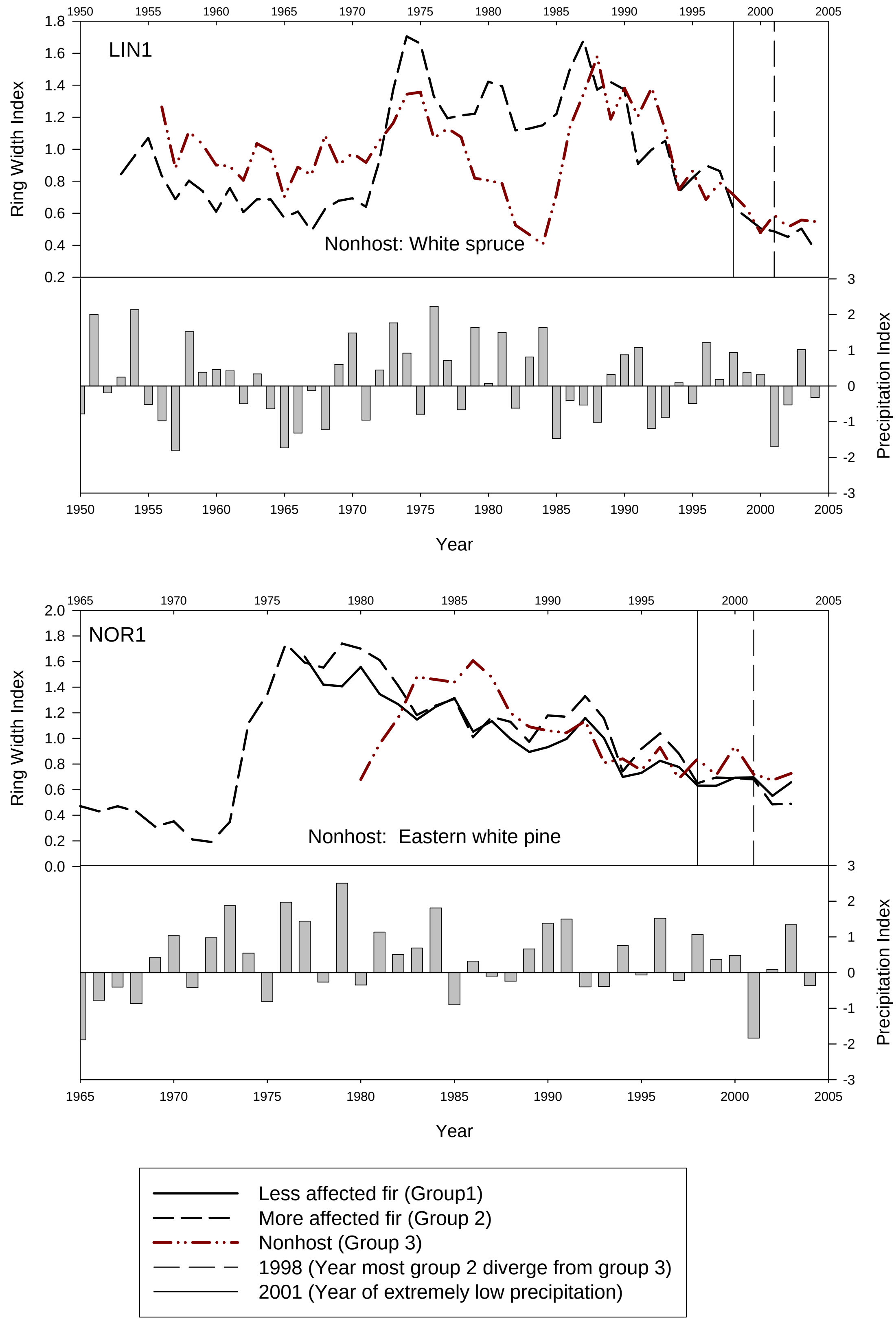
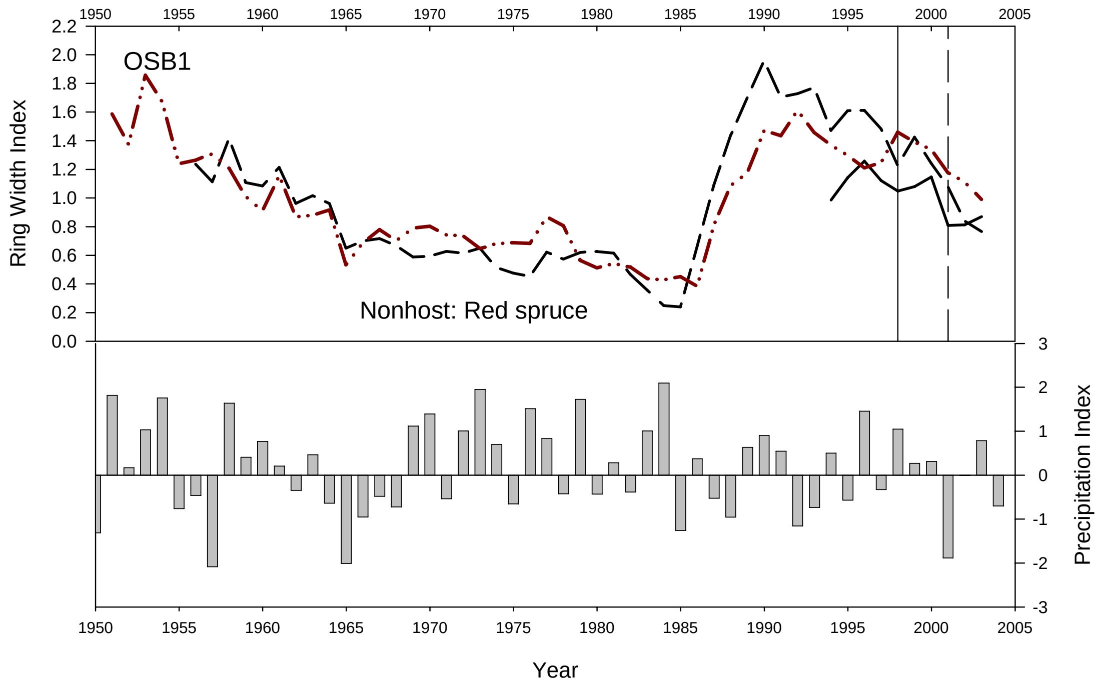


Figure C. 1 continued.



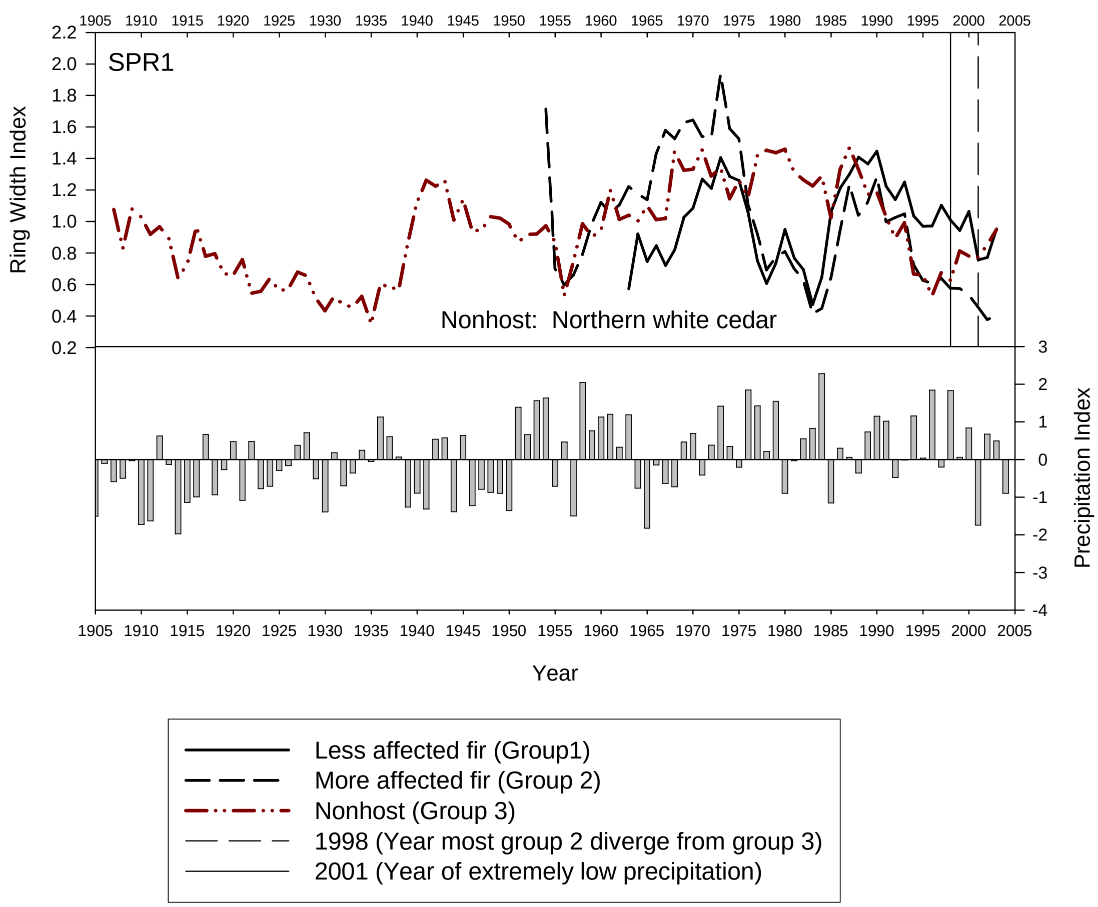


Figure C. 1 continued.

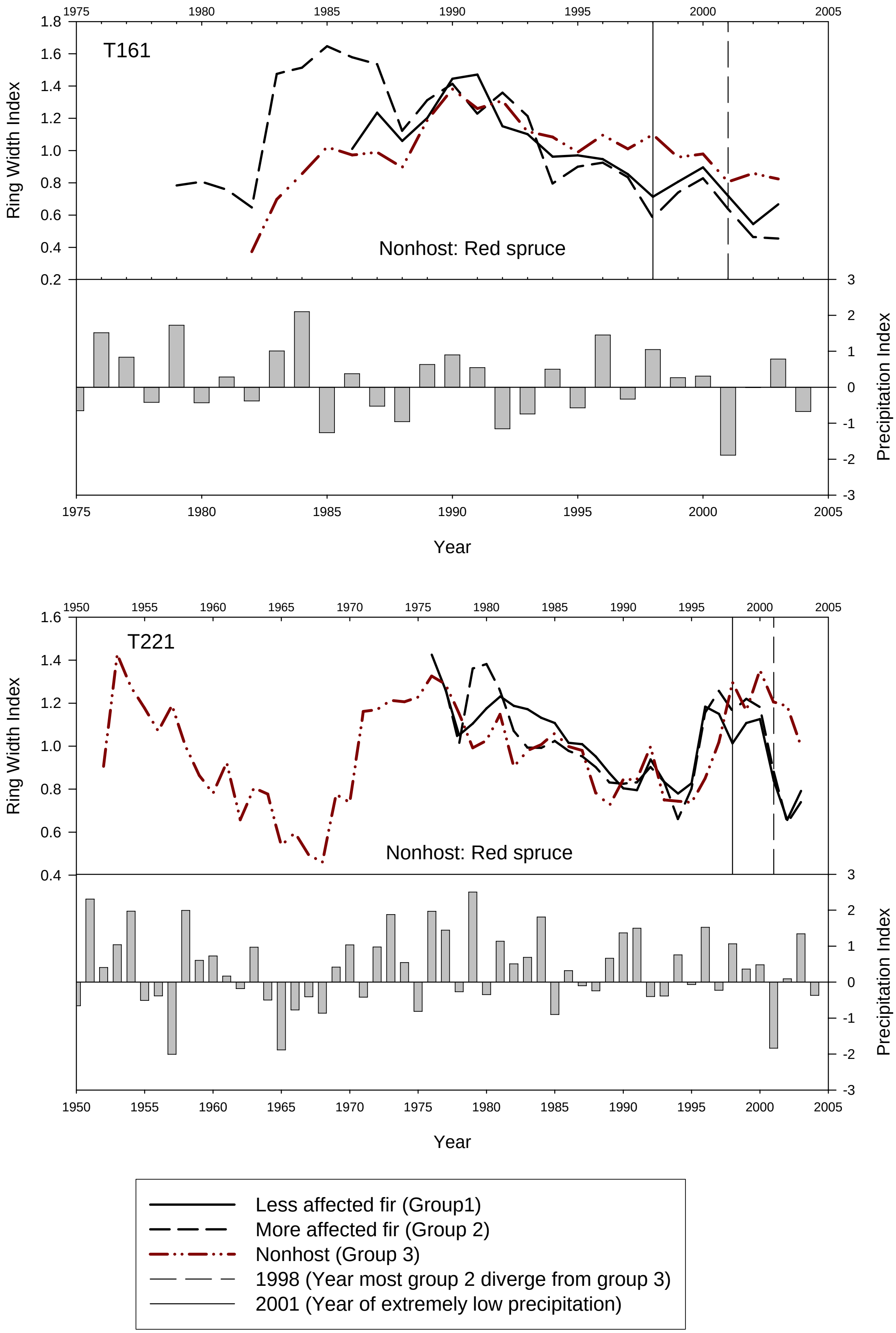


Figure C. 1 continued.

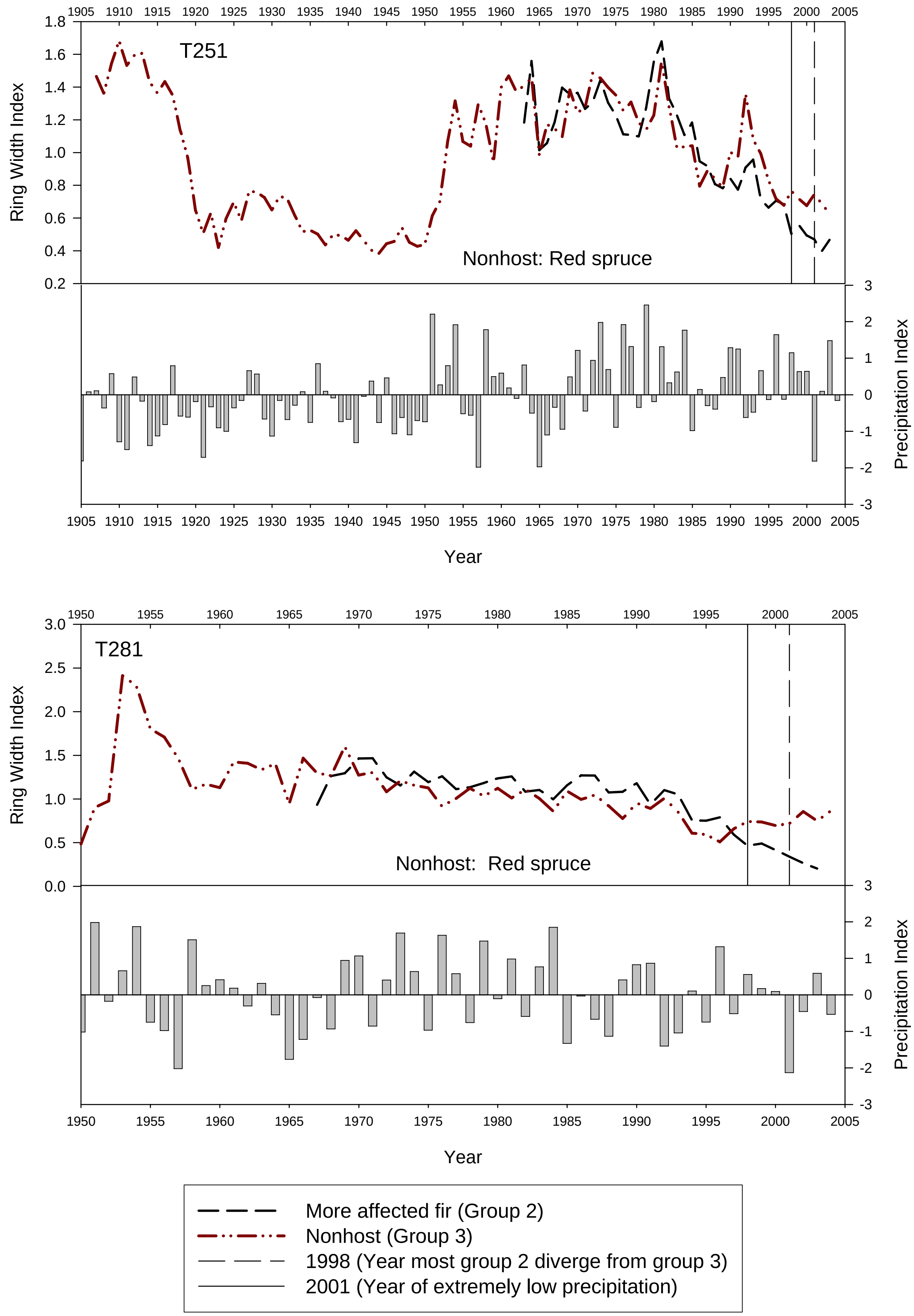


Figure C. 1 continued.

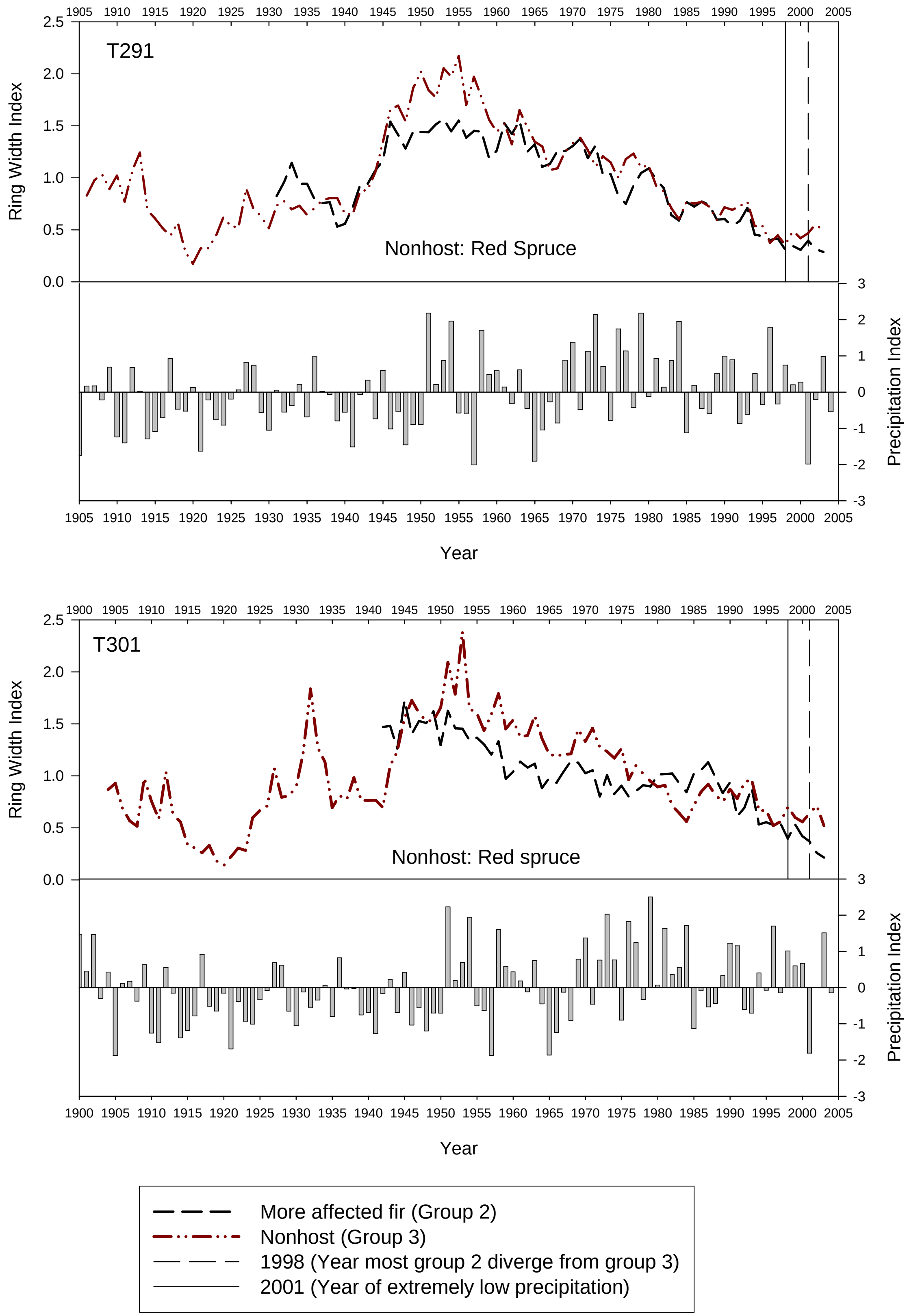


Figure C. 1 continued.

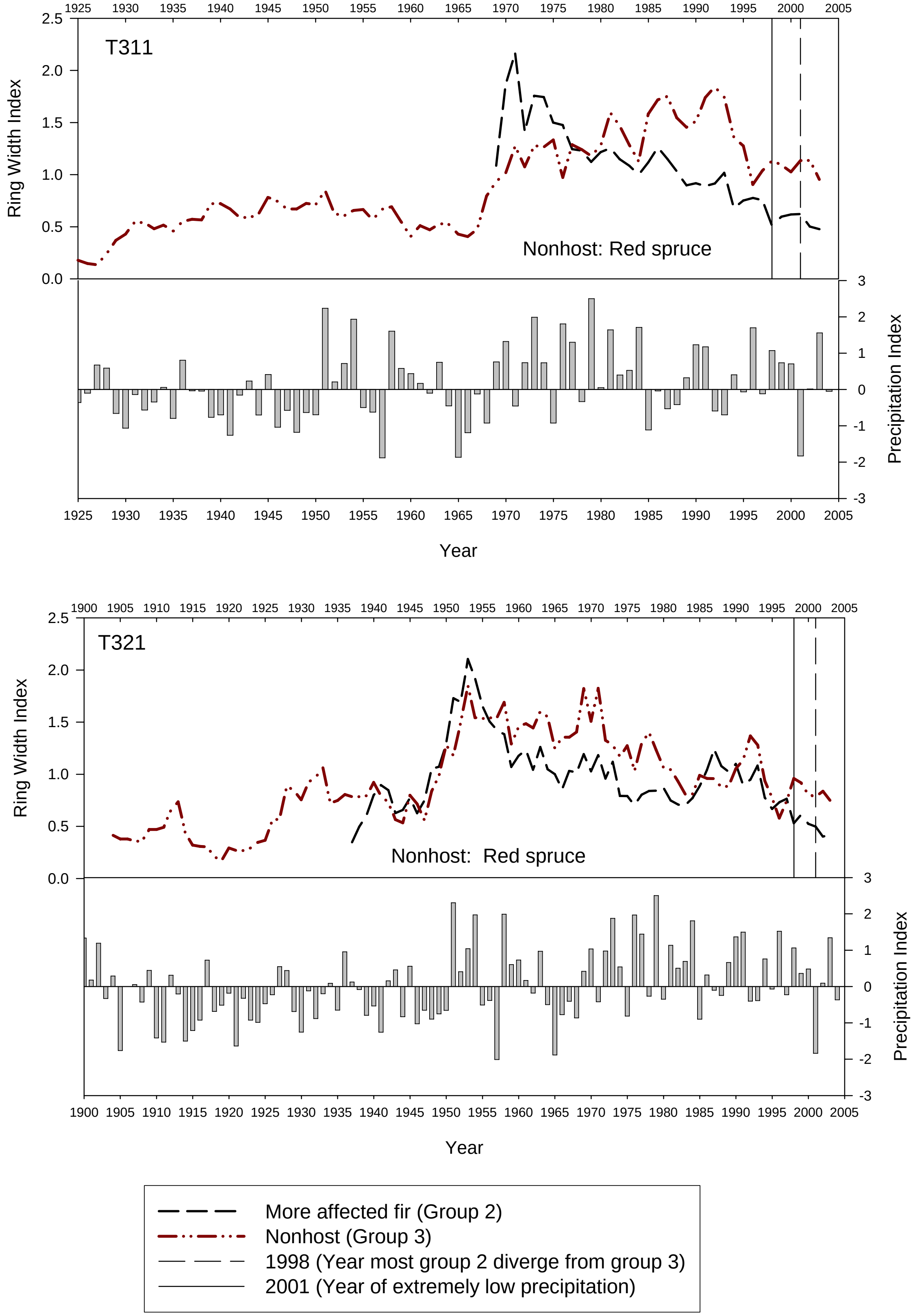


Figure C. 1 continued.

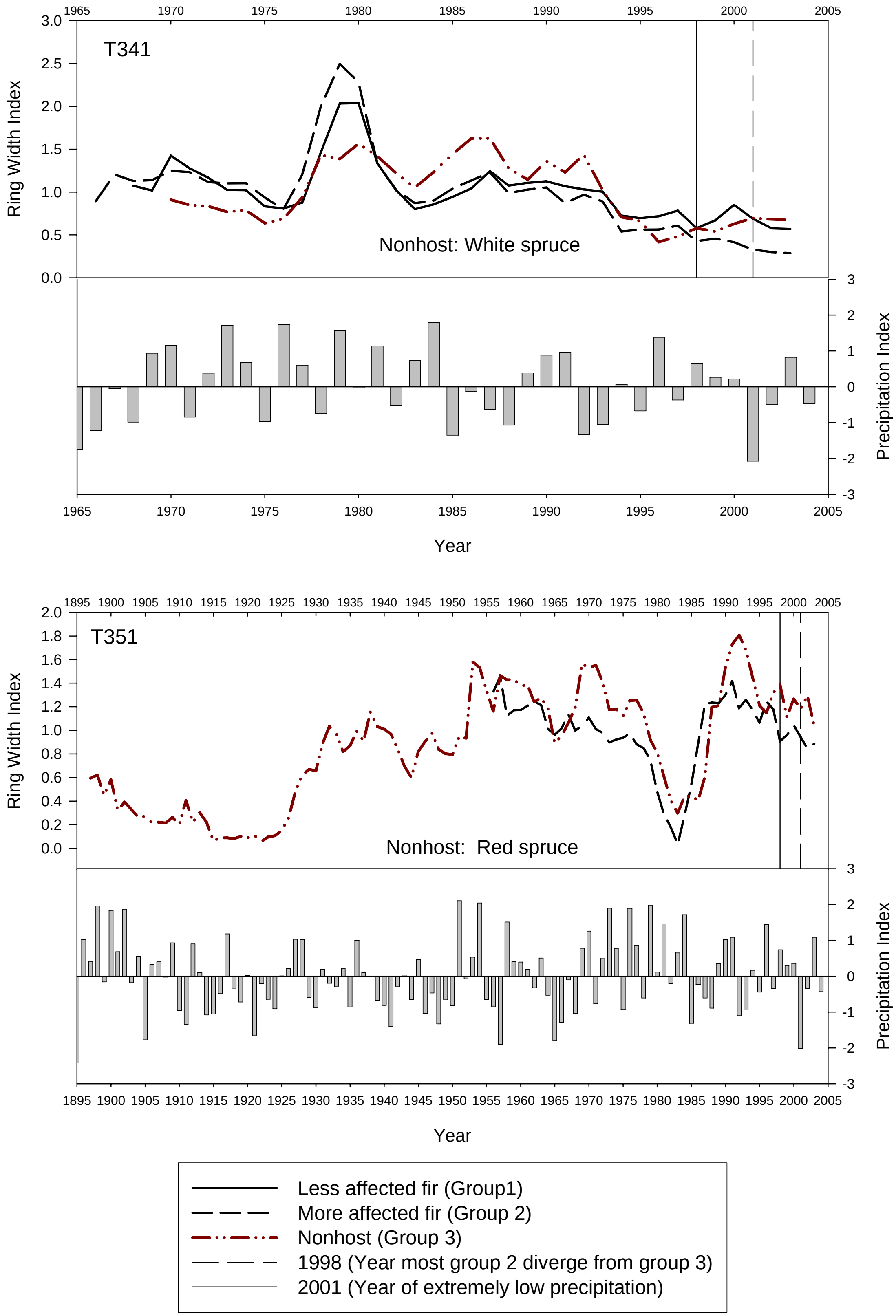


Figure C. 1 continued.

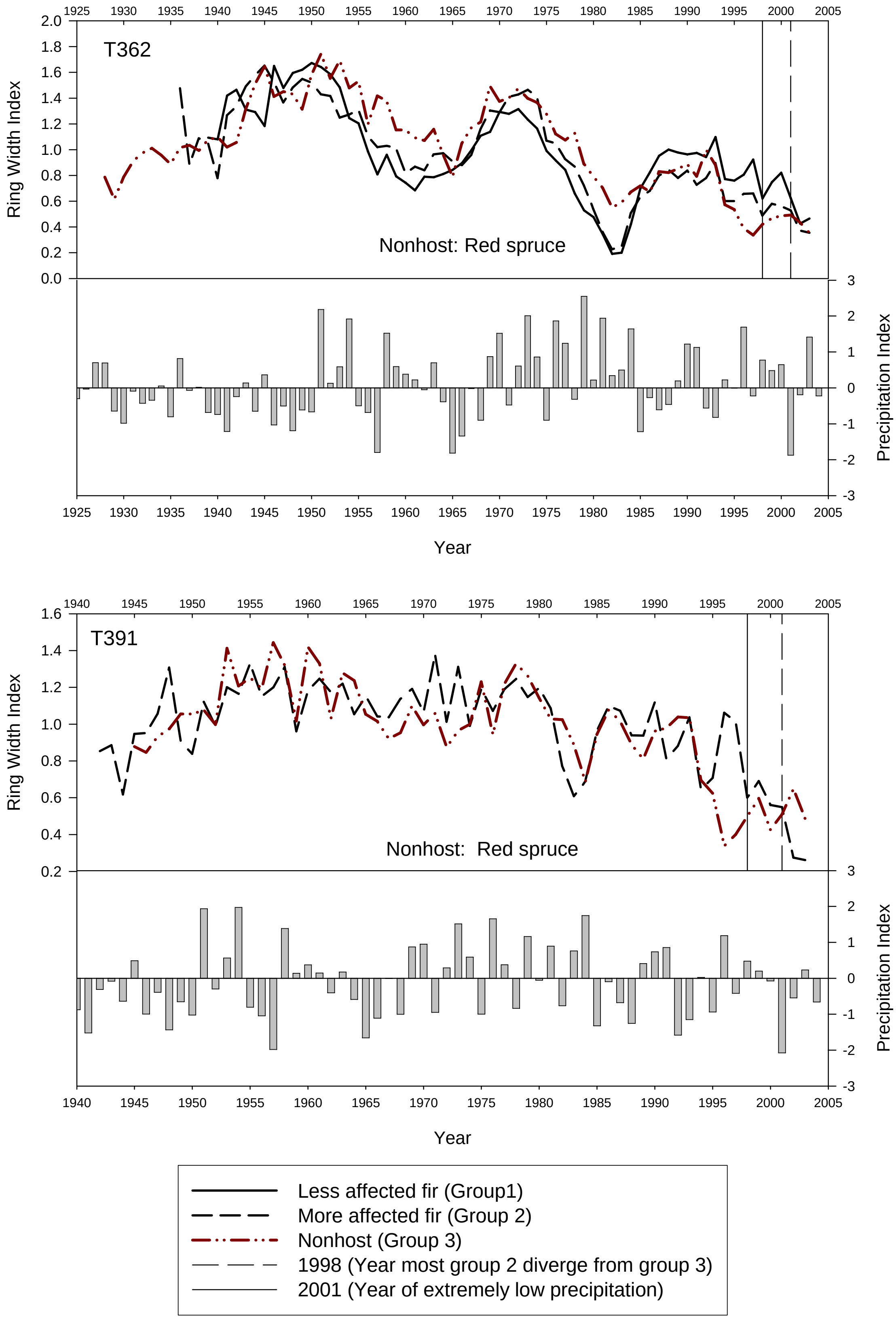


Figure C. 1 continued.

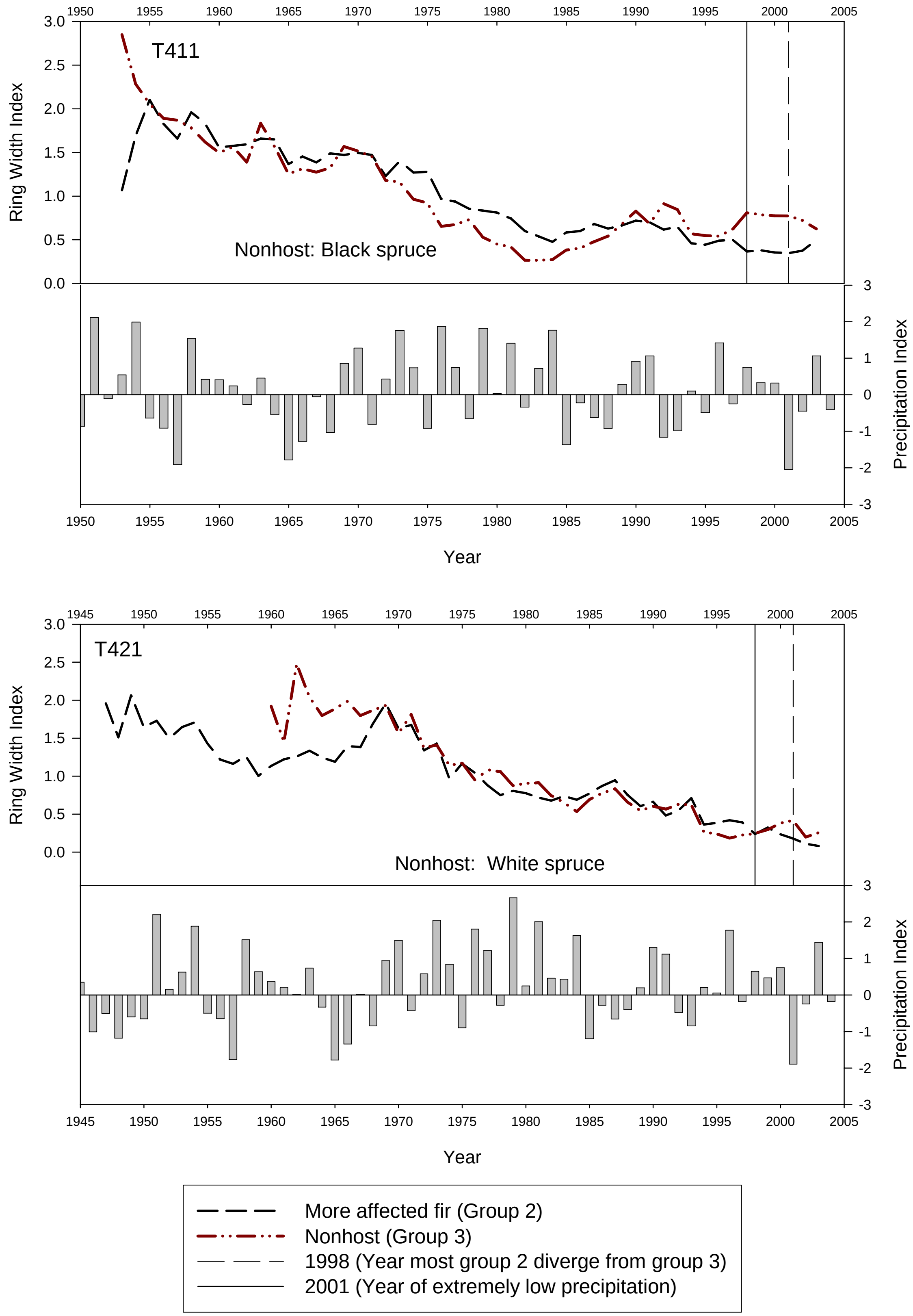


Figure C. 1 continued.

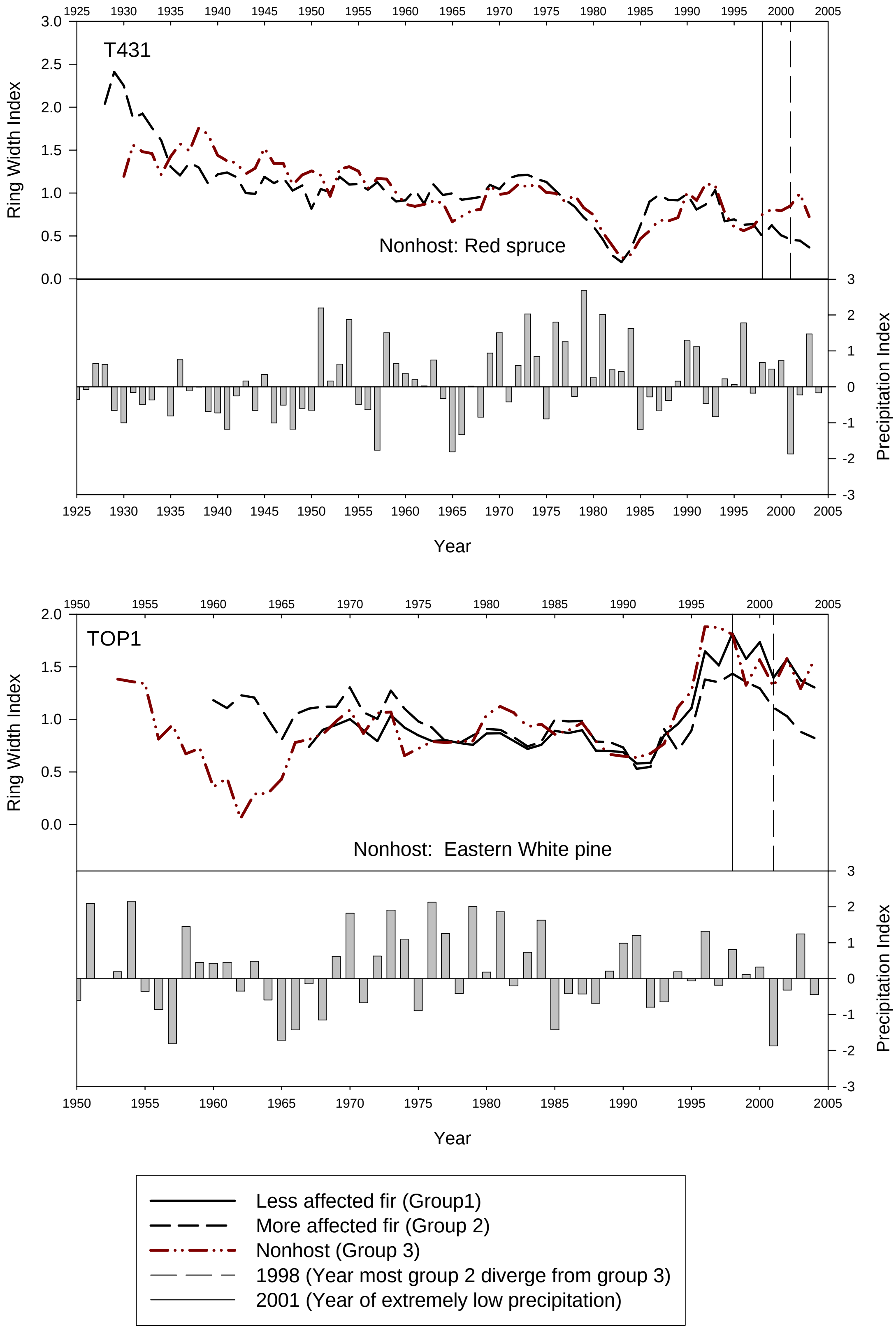


Figure C. 1 continued.

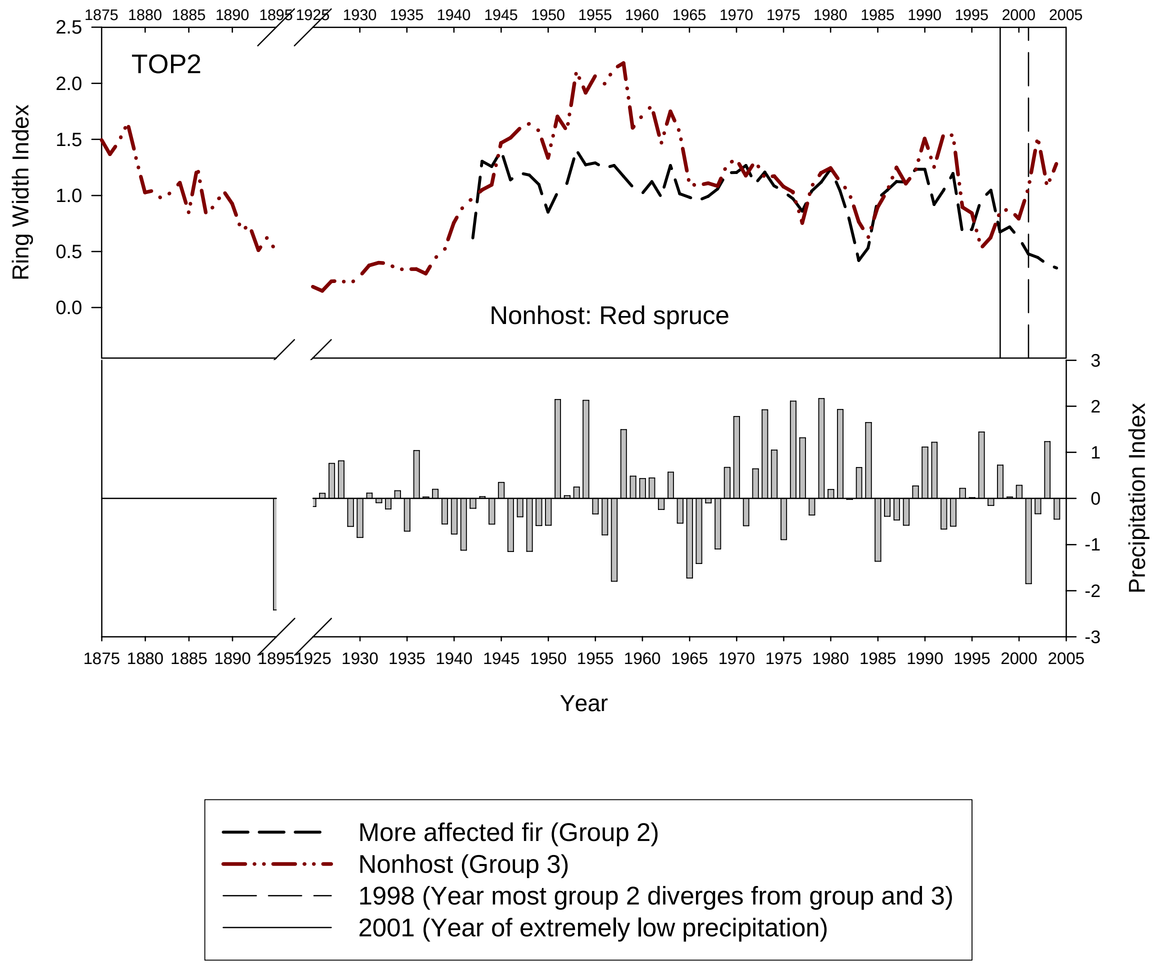


Figure C. 1 continued.

APPENDIX D
Rotholz Summary

Table D. 1. Number of trees and plots by rotholz category. Codes defined below.

	Number of Trees per Category				Number of Plots per Category			
Year	**RH Code-0**	**RH Code-1**	**RH Code-2**	**RH Code-3**	**RH Code-0**	**RH Code-1**	**RH Code-2**	**RH Code-3**
1948	144	0	1	0	28	0	1	0
1949	154	0	0	1	28	0	0	1
1950	170	0	0	1	28	0	0	1
1951	180	0	0	1	28	0	0	1
1952	197	0	0	0	29	0	0	0
1953	210	0	0	0	29	0	0	0
1954	225	0	0	0	29	0	0	0
1955	231	0	0	0	29	0	0	0
1956	245	0	0	0	29	0	0	0
1957	252	0	0	0	29	0	0	0
1958	264	0	1	0	28	0	1	0
1959	269	2	0	1	28	1	0	1
1960	279	2	0	1	27	1	0	1
1961	289	2	0	1	27	1	0	1
1962	302	2	0	1	26	2	0	1
1963	313	2	0	1	26	2	0	1
1964	323	2	1	1	25	2	1	1
1965	333	3	0	1	26	2	0	1
1966	339	3	1	1	25	2	1	1
1967	356	3	0	2	25	3	0	2
1968	364	8	0	1	25	4	0	1
1969	375	5	4	3	23	5	2	2
1970	382	5	3	7	23	4	3	3
1971	400	8	3	2	22	6	3	1
1972	414	6	1	1	24	3	1	1
1973	434	6	0	0	24	5	0	0
1974	443	4	0	1	26	3	0	1
1975	455	4	0	1	25	3	0	1
1976	465	3	0	1	26	2	0	1
1977	480	4	2	2	23	3	1	2
1978	489	5	1	4	21	4	1	3
1979	495	9	2	3	19	8	2	3
1980	498	12	3	2	19	9	3	2
1981	511	10	4	1	18	8	3	1
1982	516	11	3	1	19	9	2	1
1983	520	12	2	0	20	7	2	0
1984	518	16	3	0	18	9	3	0
1985	518	19	4	1	16	11	3	1
1986	523	18	3	2	17	9	3	2
1987	523	19	2	3	17	10	2	3
1988	527	17	5	1	18	7	5	1
1989	517	30	4	1	14	15	4	1
1990	514	28	7	5	13	13	5	3

1991	504	43	5	2	11	17	5	2
1992	494	32	12	16	9	15	7	12
1993	488	43	12	11	7	18	9	10
1994	494	51	7	3	7	20	7	3
1995	477	65	8	5	6	21	8	5
1996	458	60	23	14	6	20	17	8
1997	462	58	23	12	7	19	13	10
1998	459	61	17	17	9	19	10	11
1999	455	63	19	17	8	19	12	11
2000	438	72	25	14	5	23	13	11
2001	422	88	26	10	5	23	13	8
2002	408	80	25	14	5	22	10	10
2003	395	80	16	10	6	22	9	7
Codes: 0. Normal 1. Darkened latewood 2. Half ring with rotholz 3. Whole ring with rotholz								

Table D. 2. Number of cores with rotholz by plot and year. Cells indicate the number of fir whose cores were selected for analysis that exhibited rotholz characteristics.

Plot	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
AUR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BED1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BUR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CEN1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CHE1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
GRE1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	-	-	-	-	-	-	-	-	-	-	-	-
KOS1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	**1**
KOS2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	**1**	**1**	**2**	**2**	**1**	**1**	**1**	**2**	**2**	**2**	**2**	**3**	**2**	**2**
LIN1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NOR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OSB1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T161	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T221	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T251	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T281	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T291	-	-	-	-	-	-	-	-	-	-	-	-	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	-	-	-	-	-
T301	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	**1**	**1**	-	-	-	-	-
T311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T321	**1**	**1**	**1**	**1**	-	-	-	-	-	-	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	-
T341	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T351	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	**1**	**1**	**1**	**1**
T362	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	**1**	**1**	-	-	-
T391	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	**2**	**1**	-	-	-	-	-
T411	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T421	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1**	**2**	**5**	**6**	**6**	**4**	**3**	**1**	-	-	-
T431	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table D. 2 continued.

Plot	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
AUR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2	1	2	5	7	7	7	8	6	4	4
BED1	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	1	3	2	2	3	4	4	4	4
BUR1	-	-	-	-	-	-	-	1	1	1	1	1	2	2	3	4	5	5	5	6	6	7	8	8	9	7	5
CEN1	-	-	-	-	2	3	1	1	1	1	1	1	2	2	3	3	2	1	2	2	2	3	3	3	3	4	3
CHE1	-	-	1	2	1	1	1	2	2	2	3	3	5	5	6	5	5	2	3	5	5	4	4	3	3	2	2
GRE1	1	1	1	1	1	1	-	-	-	-	-	-	1	2	3	3	3	3	6	7	6	6	5	7	8	5	3
KOS1	1	1	2	2	2	3	6	6	5	5	5	5	6	6	4	7	7	5	5	5	5	5	6	4	4	4	1
KOS2	2	2	2	3	3	1	1	2	2	1	1	-	2	2	3	4	4	4	4	6	7	6	6	8	12	12	12
LIN1	-	-	-	-	-	-	-	-	2	2	2	1	2	2	2	2	3	3	5	5	5	6	5	8	8	6	7
NOR1	-	-	-	-	-	-	-	2	2	2	2	2	3	3	5	5	4	3	3	3	1	1	1	1	4	5	7
OSB1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	2	2	3	3	6	8	9	9	11	9
SPR1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T161	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	1	1	3	3	6	5	6	6
T221	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	6	8	7	7	6	6	6	6
T251	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T281	-	-	-	-	-	-	-	-	-	-	-	-	1	3	5	7	7	6	7	8	4	4	4	3	4	4	2
T291	-	1	1	-	-	1	1	1	1	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	2	3	-
T301	-	-	-	1	1	1	1	1	2	3	3	3	3	3	3	3	3	3	3	3	2	2	2	3	3	-	-
T311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	1	1	1	4	5	7	6
T321	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	2	2	2	3	3	3	4	4	5	3	3	2
T341	2	2	3	3	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T351	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-	-	1	2	2	3
T362	-	-	-	-	-	-	-	-	1	1	1	1	1	2	2	2	2	2	2	2	-	-	-	1	-	-	1
T391	1	1	1	1	1	1	1	1	2	2	1	2	2	3	3	3	3	4	6	8	8	9	8	5	6	1	2
T411	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	3	4	3
T421	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	-
T431	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1
TOP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	5	5	7	9	8	9	9	12	15	15
TOP2	-	1	1	2	1	2	1	1	2	2	3	3	3	2	3	4	5	5	6	6	6	4	4	3	2	2	2

Table D. 3. Age of fir by year. Only cores with a pith, or whose age to pith could be estimated were included in this analysis.

YEAR	Number with rotholz	Average Age		Maximum Age	Minimum Age
		Rings with rotholz	All rings	Rings with rotholz	Rings with rotholz
1948	1	30	12	30	30
1949	1	31	12	31	31
1950	1	32	12	32	32
1951	1	33	13	33	33
1952	0		13		
1953	0		13		
1954	0		14		
1955	0		14		
1956	0		15		
1957	0		15		
1958	1	40	16	40	40
1959	3	32	16	41	24
1960	3	33	17	42	25
1961	3	34	17	43	26
1962	3	29	18	44	15
1963	3	30	19	45	16
1964	4	44	19	85	17
1965	4	29	20	47	18
1966	5	29	20	48	19
1967	5	32	20	49	20
1968	8	31	21	50	21
1969	9	31	21	51	22
1970	12	33	22	52	23
1971	11	35	22	53	24
1972	6	33	23	41	25
1973	5	35	23	42	26
1974	4	31	24	38	27
1975	4	32	24	39	27
1976	3	30	25	32	28
1977	5	28	25	33	14
1978	7	32	26	43	15
1979	10	31	26	44	13
1980	13	32	27	43	14
1981	10	34	28	44	12
1982	12	36	29	58	12
1983	11	40	30	59	32
1984	14	40	31	60	24
1985	16	43	31	64	25
1986	15	42	32	65	26
1987	17	44	33	66	27
1988	16	45	34	67	28
1989	29	41	35	68	16
1990	33	44	36	69	17
1991	40	43	37	70	18
1992	47	42	38	70	18

Table D. 3 continued

YEAR	Number with rotholz	Average Age		Maximum Age	Minimum Age
		Rings with rotholz	All rings	Rings with rotholz	Rings with rotholz
1993	53	43	39	71	19
1994	49	45	40	72	23
1995	64	46	41	74	21
1996	82	48	42	78	17
1997	81	47	43	79	18
1998	84	46	44	80	14
1999	90	47	45	81	15
2000	99	47	46	82	14
2001	113	47	47	80	15
2002	107	46	47	81	16
2003	95	45	48	82	17
Average	-	37	27	50	21

Biography of the Author

Allison Kanoti (Bush) was born in Niagara Falls, New York on May 7th 1974. She moved to Piermont, New Hampshire at the age of 2. She grew up with her older sister Sara and younger brother Matt on both sides of the river in New Hampshire and Vermont's Upper Valley. Her parents were her first guides in the natural world—her siblings and four-legged fur-covered friends were companions in exploration. Further introduction to the natural world came from a series of teachers and mentors including the teachers at Open Fields School in Thetford, Vermont; her 9th grade science teacher, Fred Rubinfeld; summer camp instructors at Vermont Technical College (VTC) and the University of Vermont (UVM); and Virginia Barlow, who allowed a shy 11th-grade student to shadow her for a day.

Allison attended Oxbow Union High School in Bradford, Vermont. In 1991 she participated in VTC's Vermont Academy of Science and Technology where she completed her last year of high school and first year towards an Associate of Engineering degree in Civil Engineering Technology. She graduated from VTC in 1993, at which point she began work on a Bachelor of Science degree in Forest Biology at UVM. She graduated from UVM in 1996. In the fall of 1996 she began work with the US Forest Service, Forest Inventory and Analysis where she met her husband, Keith. She worked for the US Forest Service until 2001, when she moved to Maine and began work with the Maine Forest Service. In 2003 Allison and Keith bought a house, got married, adopted a dog and started graduate school. At the University of Maine Allison was the recipient of The Provost Fellowship and The Mark W. Houseweart Award. Allison is a candidate for the Master of Science degree in Forestry from The University of Maine in May, 2006.